Welding in the World (2020) 64:1681–1689
https://doi.org/10.1007/s40194-020-00946-8

RESEARCH PAPER

Validation of the fatigue strength assessment of HFMI-treated steel joints under variable amplitude loading

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Received: 6 September 2019 / Accepted: 15 June 2020 / Published online: 23 June 2020

Abstract

A recommendation for the application and fatigue assessment of the HFMI post-treatment was published by the IIW in 2016. Recently, the therein recommended HFMI design curves in case of constant amplitude loading (CAL) were validated involving test data with different base material yield strengths, increased plate thicknesses, and elevated load ratios. Continuative to this previous work, this paper focuses on the fatigue assessment of HFMI-treated steel joints under variable amplitude loading (VAL). Four test data sets including randomly distributed VAL and a sufficient amount of tested specimens to ensure a statistically verified assessment are investigated. It is shown that an application of the recommended equivalent stress range approach and a further comparison of the test results to the design curves under CAL lead to a conservative fatigue assessment if the recommended value of the specified damage sum of $D = 0.5$ is used. Furthermore, an increased value of $D = 1.0$ still maintains a conservative design as presented in the study. Based on this work involving the analysed data sets, it can be concluded that the recommended procedure is well applicable and a conservative fatigue design is facilitated.

Keywords Fatigue strength · Welded joint · Steel · HFMI treatment · Variable amplitude loading · Equivalent stress range · Specified damage sum

1 Introduction

The fatigue strength of welded steel joints is generally independent of the base material's yield strength, see IIW recommendation [1]. The application of post-weld-treatment techniques, like the HFMI treatment, is well applicable in order to utilize the lightweight potential of high-strength steel materials [2]. Guidelines for the fatigue assessment [3] under both constant (CAL) [4] and variable amplitude loading (VAL) [5], as well as for quality assurance [6], are developed and published as IIW recommendation for the HFMI treatment [7].

Recently, the applicability of this guideline for the fatigue strength assessment of HFMI-treated steel joints under CAL incorporating increased yield strengths, R-ratios, and plate thicknesses is validated by numerous fatigue tests data sets, see [8, 9]. In case of VAL, Palmgren [10] and Miner [11] proposed a linear damage accumulation, whereas a damage sum D of $D = 0.5$ is conservatively recommended in [1, 7].

In [12], a study including medium- and high-strength steel joints tested under VAL shows that the real damage sum D_{real} exhibits a value of $1/3 < D_{real} < 3$ for most of the analysed data. In case of fluctuating mean stress states, even a lower damage sum of $D = 0.2$ is investigated in [13], which is also noted in [1]. In order to assess the fatigue strength under VAL utilizing the recommended fatigue design values in [1], an equivalent stress range $\Delta\sigma_{eq}$ can be calculated, see Eq. 1.

$$\Delta\sigma_{eq} = \sqrt[m]{\frac{1}{D}\cdot\frac{\sum\left(n_i\cdot\Delta\sigma_i^m\right) + \Delta\sigma_L^{(m-m')}\cdot\sum\left(n_j\cdot\Delta\sigma_j^{m'}\right)}{\sum n_i + \sum n_j}} \quad (1)$$

Thereby, D is the specified damage sum, $\Delta\sigma_i$ is the stress range and m is the slope above the knee point of the S/N-

Recommended for publication by Commission XIII - Fatigue of Welded Components and Structures

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Table 1 Overview of fatigue test data sets

Data set	Reference	Specimen type	Yield strength (MPa)	Plate thickn. (mm)	R-ratio (−)	Load spectrum
No. 1	[19]	Long. stiffener	S355	5	0.1	Straight line
No. 2	[20]	Long. stiffener	S700	8	− 1	Straight line
No. 3	[21]	Butt joint	S1100	6	0.1	Straight line
No. 4	[21]	Butt joint	S1100	6	0.1	Gaussian

curve, $\Delta\sigma_j$ is the stress range and m' is the slope below the knee point of the S/N-curve, n_i is the number of load cycles applied at $\Delta\sigma_i$, n_j is the number of load cycles applied at $\Delta\sigma_j$, and $\Delta\sigma_L$ is the stress range at the knee point of the S/N-curve. For VAL, it is assumed to use $m' = 2\cdot m-1$ instead of the value of $m' = 22$ applicable for CAL [1, 14]. Previously published studies [15–18] demonstrate that the specified damage sum D for such post-weld-treated steel weld joints varies between 0.2 and 1.0, which maintains a validation of the recommended procedure for a fatigue assessment of HFMI-treated mild- and high-strength steel joints given in [7]. Therefore, this paper focuses on the applicability of the equivalent stress range approach considering specified damage sums in order to validate the fatigue assessment of HFMI-treated steel joints up to a nominal yield strength of $f_y = 1100$ MPa of the base material.

2 Test data

In Table 1, the VAL fatigue test data [19–21] used for the validation in this paper is presented. Focus is laid on test data, which includes randomly distributed VAL as well as a sufficient amount of tested specimens to ensure a statistically verified assessment. All cyclic experiments are performed under uni-axial loading at a load ratio of $R = 0.1$ (with tensile mean stress) or $R = -1$ (without mean stress). Two different load spectra, namely straight line or Gaussian distribution, are incorporated. Thereby, the straight line spectrum exhibits a shape exponent of $\nu = 1$ and the Gaussian spectrum a value of $\nu = 2.6$, both with $H_0 = 2\cdot10^5$ load cycles, see Eq. 2 [22]. Further details to VAL fatigue tests are provided in [23].

$$\ln H_i = [1-(\Delta\sigma_i/\Delta\sigma_{\max})^{\nu}]\cdot\ln H_0 \tag{2}$$

where H_i is the cumulative frequency of load cycles for $\Delta\sigma_i$, H_0 is the block size, and ν is the shape exponent.

Detailed information about the weld specimen geometries, mechanical properties of the base material, HFMI treatment and the VAL testing procedure is given in each reference. In this study, the presented fatigue test data points of each reference are taken as basis for a further evaluation of the equivalent stress range and a final comparison with the recommended fatigue design curve given by the IIW recommendation for the HFMI treatment [7]. Thereby, only the effect of the increased base material strength is considered and no further influences, such as an increased plate thickness or R-ratio, need to be taken into account. These further effects are validated in [8, 9] for HFMI-treated steel joints under CAL as aforementioned.

3 Results

3.1 Fatigue test results under CAL and VAL

The fatigue test results of data set no. 1 are shown in Fig. 1 depicted with the maximum nominal stress range. The

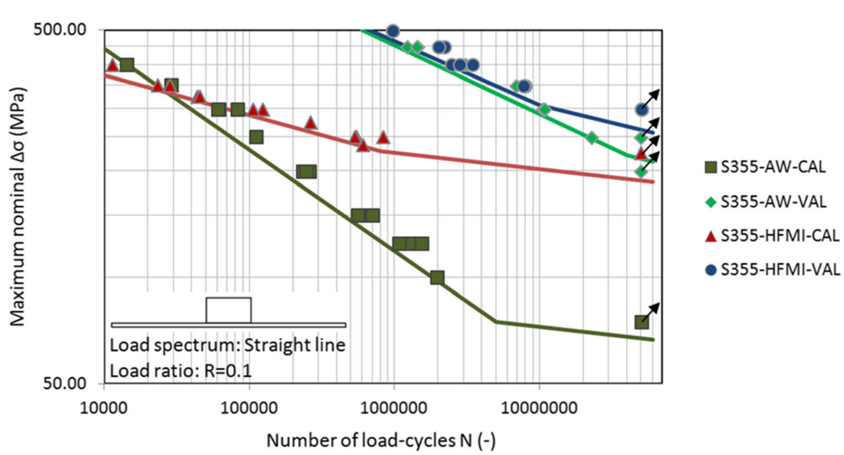

Fig. 1 Fatigue test results of data set no. 1 (maximum nominal stress range)

Table 2 S/N-curve parameters of data set no. 1

Test series	$\Delta\sigma$ (N = 2e6) (MPa)	$\Delta\sigma$ (N = 5e7) (MPa)	Slope m (−)	Scatter 1/Tσ (−)
S355-AW-CAL	97	67	3.5	1.15
S355-AW-VAL	396	217	5.2	1.09
S355-HFMI-CAL	204	186	8.8	1.07
S355-HFMI-VAL	412	262	5.5	1.09

statistical analysis is performed by applying the standardized procedure given in [24] evaluating the S/N-curve at a survival probability of 97.7%. For the high-cycle fatigue strength with load cycles above the knee point N_k, a second slope of $m' = 22$ in case of CAL and of $m' = 5$ for VAL is applied [1]. Table 2 provides an overview of the statistically evaluated S/N-curve parameters. As the tests are conducted up to a number of fifty million load cycles, the endurable nominal stress range $\Delta\sigma$ is evaluated also at this level accordingly.

The fatigue test results of data set no. 1 reveal a significant increase of the high-cycle fatigue strength under CAL by a factor of about 2.1 at $N = 2e6$ load cycles. In addition, the slope in the finite life regime under CAL increases due to the HFMI treatment, which is in line with the IIW recommendations [1, 7]. On the contrary, a reduced beneficial effect of the HFMI treatment is observable under VAL. Thereby, a fatigue strength increase of a factor of about 1.04 at 2e6 load cycles due to the post-treatment is observed; however, at 5e7 load-cycles, a slightly enhanced benefit of roughly 1.2 is evaluated. As presented in [19] and furthermore investigated in [25], this reduced effect can be majorly drawn to a certain relaxation of the HFMI-induced compressive residual stress state during cyclic loading.

The fatigue test results of data set no. 2 are shown in Fig. 2 depicted with the maximum nominal stress range. Table 3 provides an overview of the statistically evaluated S/N-curve parameters. As the tests are conducted only within the finite life regime, the endurable nominal stress range $\Delta\sigma$ is evaluated only at a defined number of two million load cycles, which thereby equals the FAT-class. In this case, again a fundamental increase of the fatigue strength due to the HFMI treatment is evaluated under CAL. Thereby, an increase by a factor of about 3.4 in fatigue strength at 2e6 load cycles is observable. However, under VAL, again a reduced benefit by the post-treatment is investigated leading to an increase factor of about 1.3 at 2e6 load cycles, whereas the tendency is in line with data set no. 1. The evaluated slopes again fit well to the recommended values.

The fatigue test results of data set no. 3 are shown in Fig. 3 and the results of data set no. 4 are depicted in Fig. 4 with the maximum nominal stress range. Tables 4 and 5 provide an overview of the statistically evaluated S/N-curve parameters of the two data sets. In detail, under CAL, an increase of a factor of about 1.3 for data set no. 3 and no. 4 is observed at 2e6 load cycles. Under VAL, this factor equals about 1.1 for data set no. 3 and roughly 1.6 for data set no. 4 again at 2e6 load cycles. As the run-outs are basically in line with the fatigue test data points in the finite life regime, no knee point is conservatively considered in case of both test series under VAL. In general, the benefit due to HFMI may be reduced for butt joints exhibiting a comparably low stress concentration at the weld toe already leading to a comparably high fatigue strength in the AW condition. In addition, it may be assumed that due to the use of the ultrahigh-strength steel and comparably mildly notched butt joint geometry, no relaxation of the compressive residual stress state as in case of the previous two data sets occurs, which may explain this outcome. Further analysis is scheduled to clarify this behaviour.

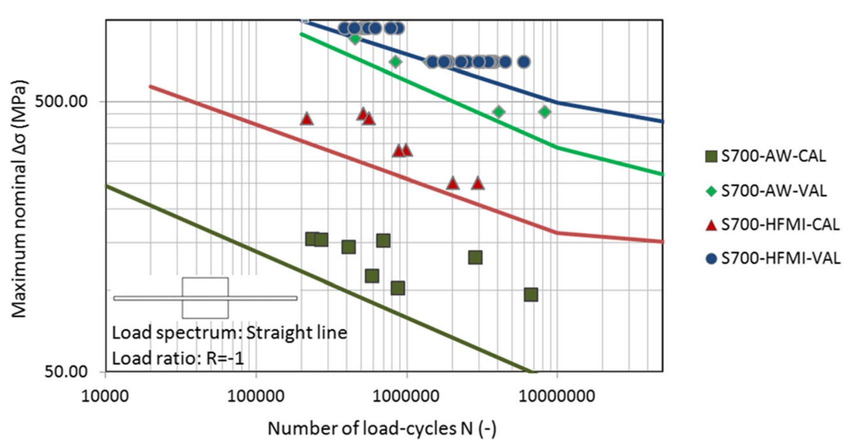

Fig. 2 Fatigue test results of data set no. 2 (maximum nominal stress range)

Table 3 S/N-curve parameters of data set no. 2

Test series	Δσ (N = 2e6) (MPa)	Slope m (−)	Scatter 1/Tσ (−)
S700-AW-CAL	67	4.1	1.76
S700-AW-VAL	502	4.0	1.26
S700-HFMI-CAL	226	5.0	1.39
S700-HFMI-VAL	659	5.6	1.17

3.2 Fatigue assessment of HFMI-treated joints under VAL

As introduced, main focus of this work is to validate the applicability of the equivalent stress range approach for HFMI-treated steel joints under VAL. Therefore, Eq. 1 is used to calculate the equivalent nominal stress range of the VAL test data for the HFMI-treated joints. For the calculation, the recommended slope $m = 5.0$ and $m' = 9$ is considered. The stress range at the knee point of the S/N-curve is evaluated according to the applicable design curve based on the IIW recommendations for the HFMI treatment [7]. Herein, it is mentioned that a specified damage sum of $D = 0.5$ may be used for the assessment. For comparison purpose, additionally a value of $D = 1.0$ is applied within this study. Utilizing these values and the data from each load spectra, the equivalent nominal stress range for each fatigue test data point is evaluated. Finally, the S/N-curve for a survival probability of 97.7% is statistically evaluated and compared with the applicable design curve for the HFMI-treated joint under CAL.

Figure 5 illustrates the results of the fatigue assessment of data set no. 1 using a damage sum of $D = 0.5$. For the S355 longitudinal stiffener, a design curve of FAT 112 is applicable under CAL according to [7]. Applying the equivalent stress range approach and the value of $D = 0.5$, the resulting S/N-curve is assessed conservatively with a FAT-class of FAT 174 and a slope of 7.2. Therefore, the recommended use of the equivalent stress range approach with $D = 0.5$ is validated in this case.

Figure 6 depicts the results of the fatigue assessment of data set no. 1 using an increased damage sum of $D = 1.0$. Again, applying the equivalent stress range approach and the value of $D = 1.0$, the resulting S/N-curve is still assessed conservative-

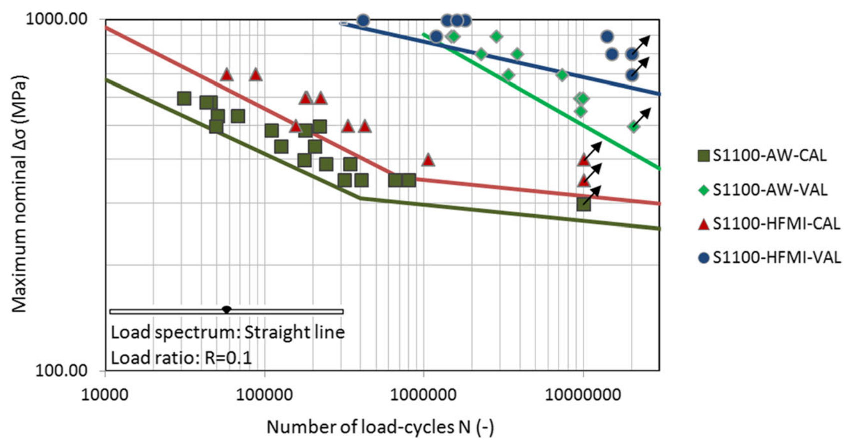

Fig. 3 Fatigue test results of data set no. 3 (maximum nominal stress range)

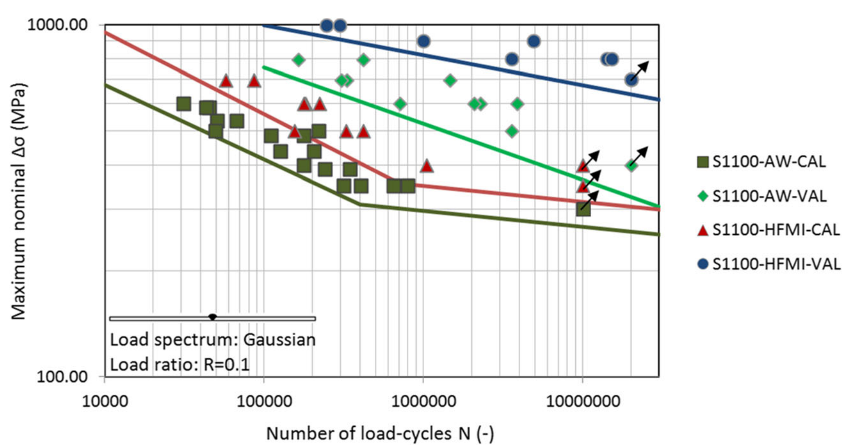

Fig. 4 Fatigue test results of data set no. 4 (maximum nominal stress range)

Table 4 S/N-curve parameters of data set no. 3

Test series	$\Delta\sigma$ ($N=2e6$) (MPa)	Slope m (−)	Scatter 1/Tσ (−)
S1100-AW-CAL	220	4.7	1.24
S1100-AW-VAL	757	3.9	1.22
S1100-HFMI-CAL	278	4.3	1.25
S1100-HFMI-VAL	808	9.9	1.25

Table 5 S/N-curve parameters of data set no. 4

Test series	$\Delta\sigma$ ($N=2e6$) (MPa)	Slope m (−)	Scatter 1/Tσ (−)
S1100-AW-CAL	220	4.7	1.24
S1100-AW-VAL	470	6.3	1.30
S1100-HFMI-CAL	278	4.3	1.25
S1100-HFMI-VAL	774	11.6	1.18

ly with a FAT-class of FAT 151 and a slope of 7.2. Hence, in this case, also a higher damage sum value of $D = 1.0$ may be feasible.

Figure 7 shows the results of the fatigue assessment of data set no. 2 using a damage sum of $D = 0.5$. For the S700 longitudinal stiffener, a design curve of FAT 125 is applicable under CAL according to [7]. Applying the equivalent stress range approach and the value of $D = 0.5$, the resulting S/N-curve is assessed conservatively with a FAT-class of FAT 214 and a slope of 5.6. Therefore, the recommended use of the equivalent stress range approach with $D = 0.5$ is again validated in this case.

Figure 8 depicts the results of the fatigue assessment of data set no. 2 using an increased damage sum of $D = 1.0$. Again, applying the equivalent stress range approach and the value of $D = 1.0$, the resulting S/N-curve is still assessed conservatively with a FAT-class of FAT 186 and a slope of 5.6. Hence, in this case, also a higher damage sum value of $D = 1.0$ may be again feasible.

Figure 9 depicts the results of the fatigue assessment of data set no. 3 using a damage sum of $D = 0.5$. For the S1100 butt joint, a design curve of FAT 180 is applicable under CAL according to [7]. Applying the equivalent stress range approach and the value of $D = 0.5$, the resulting S/N-curve is assessed conservatively with a FAT-class of FAT 302 and a slope of 9.9. Therefore, the recommended use of the equivalent stress range approach with $D = 0.5$ is again validated in this case.

Figure 10 shows the results of the fatigue assessment of data set no. 3 using an increased damage sum of $D = 1.0$. Again, applying the equivalent stress range approach and the value of $D = 1.0$, the resulting S/N-curve is still assessed conservatively with a FAT-class of FAT 263 and a slope of 5.6. Hence, in this case, also a higher damage sum value of $D = 1.0$ may be again feasible.

Figure 11 depicts the results of the fatigue assessment of data set no. 4 using a damage sum of $D = 0.5$. For the S1100 butt joint, again a design curve of FAT 180 is applicable under CAL according to [7]. Applying the equivalent stress range approach and the value of $D = 0.5$, the resulting S/N-curve is assessed conservatively with a FAT-class of FAT 414 and a slope of 11.6. Therefore, the recommended use of the equivalent stress range approach with $D = 0.5$ is again validated in this case.

Figure 12 shows the results of the fatigue assessment of data set no. 4 using an increased damage sum of $D = 1.0$. Again, applying the equivalent stress range approach and the value of $D = 1.0$, the resulting S/N-curve is still assessed conservatively with a FAT-class of FAT 360 and a slope of 5.6. Hence, in this case, also a higher damage sum value of $D = 1.0$ may be again feasible.

To sum up, the equivalent stress range approach using a specified damage sum of $D = 0.5$ as well as $D = 1.0$ leads to a conservative assessment for all analysed data sets. As presented in [19], if not the recommended design curve under CAL is

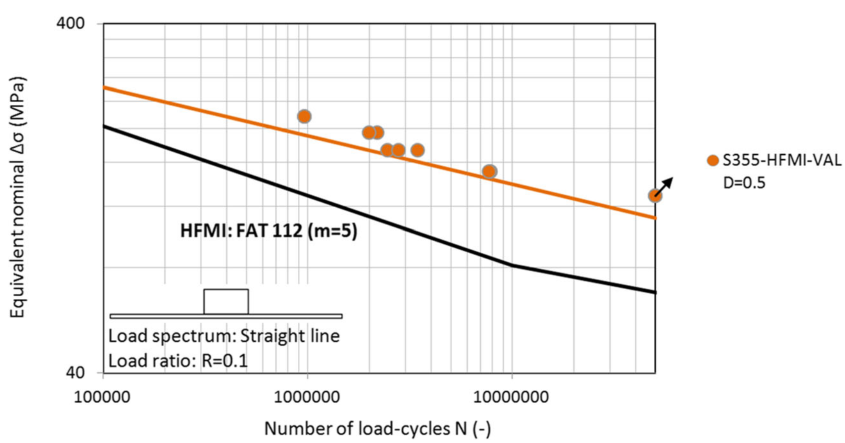

Fig. 5 Fatigue assessment of data set no. 1 (equivalent nominal stress range). Specified damage sum $D = 0.5$

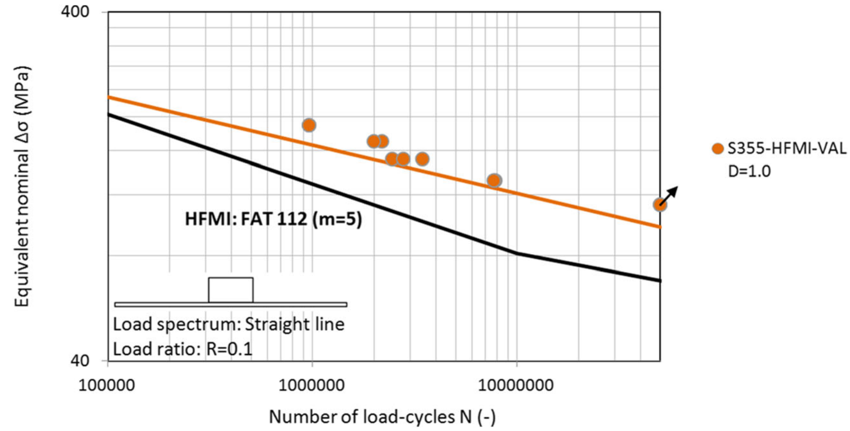

Fig. 6 Fatigue assessment of data set no. 1 (equivalent nominal stress range). Specified damage sum $D = 1.0$

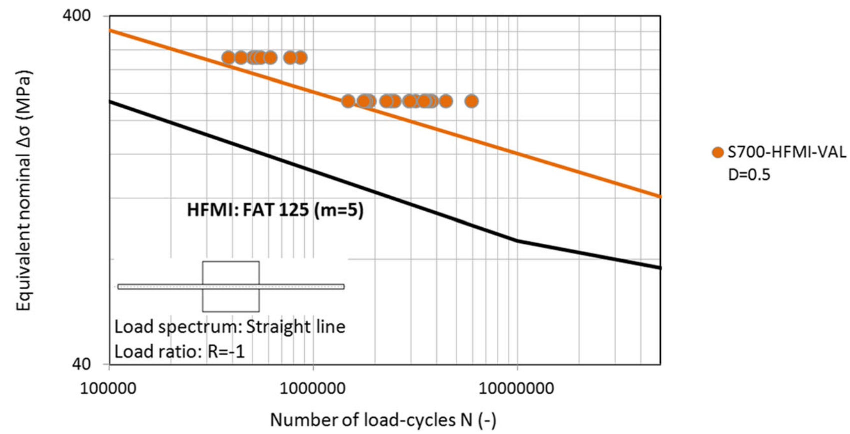

Fig. 7 Fatigue assessment of data set no. 2 (equivalent nominal stress range). Specified damage sum $D = 0.5$

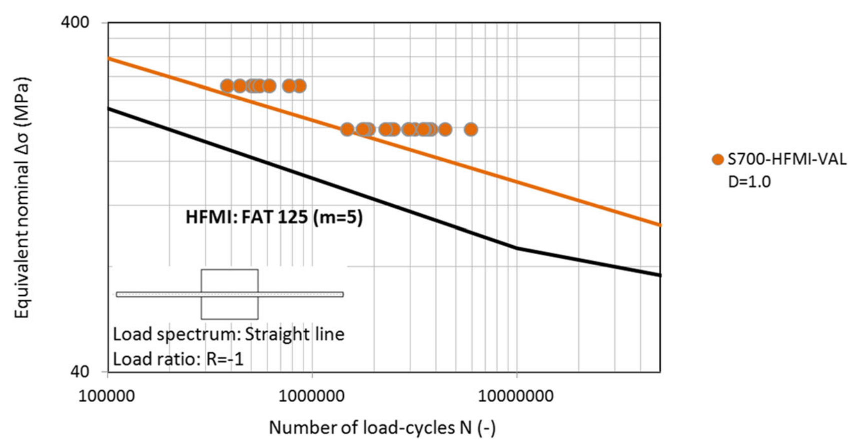

Fig. 8 Fatigue assessment of data set no. 2 (equivalent nominal stress range). Specified damage sum $D = 1.0$

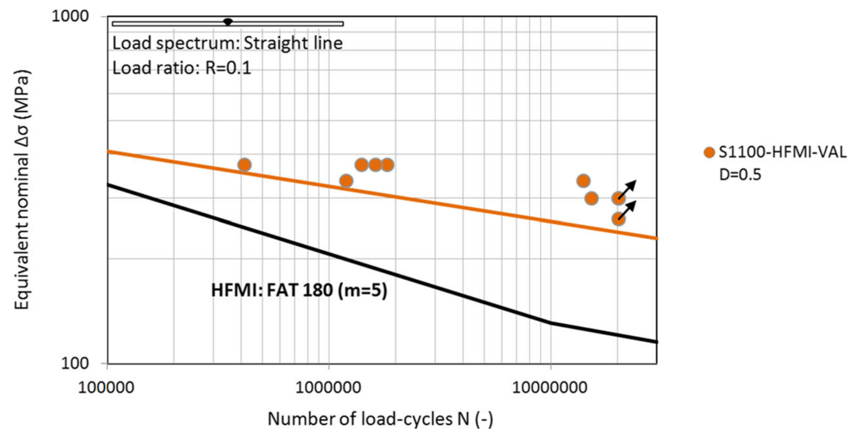

Fig. 9 Fatigue assessment of data set no. 3 (equivalent nominal stress range). Specified damage sum $D = 0.5$

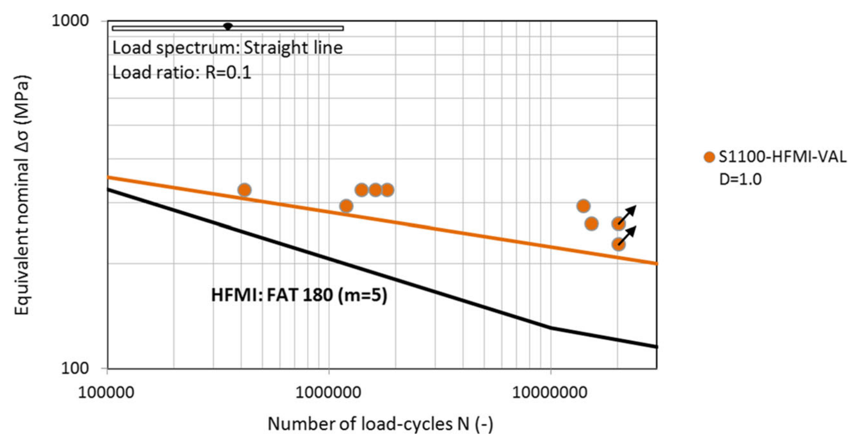

Fig. 10 Fatigue assessment of data set no. 3 (equivalent nominal stress range). Specified damage sum $D = 1.0$

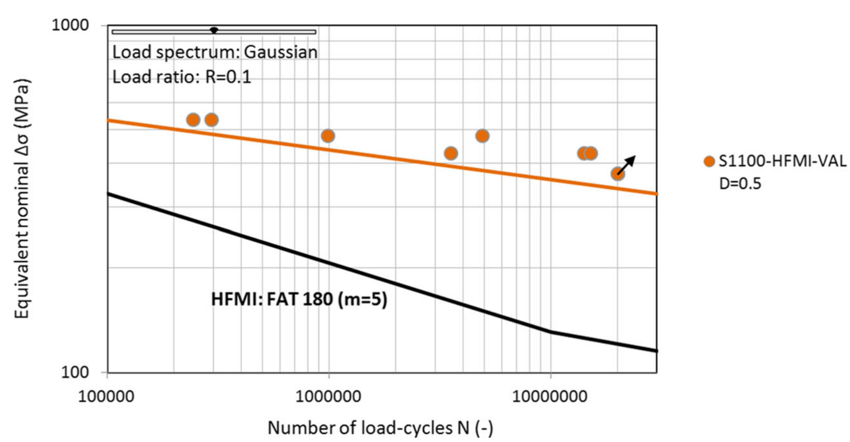

Fig. 11 Fatigue assessment of data set no. 4 (equivalent nominal stress range). Specified damage sum $D = 0.5$

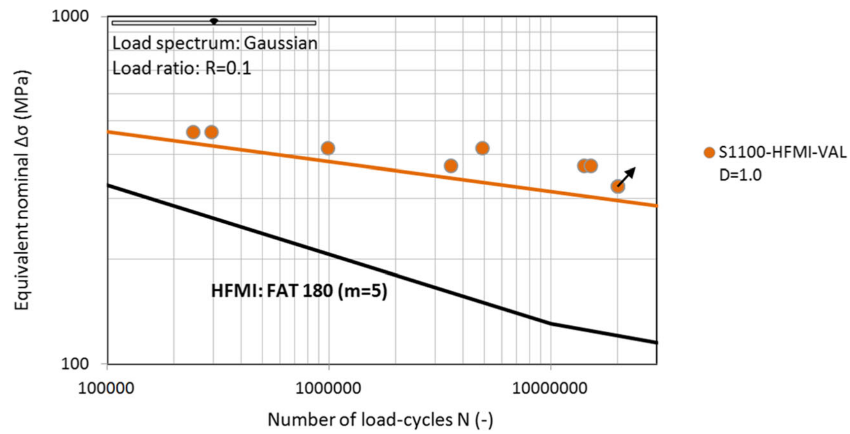

Fig. 12 Fatigue assessment of data set no. 4 (equivalent nominal stress range). Specified damage sum $D = 1.0$

used as basis for the calculation, but an experimentally evaluated S/N-curve, the damage sum values may be reduced down to $D = 0.3$ or even to $D = 0.2$ in case of fluctuating mean stress states as also noted in [1].

4 Conclusions

This paper aims to validate the applicability of the IIW recommendations for the HFMI treatment in case of HFMI-treated steel joints under VAL. Focus is laid on test data, which includes randomly distributed VAL as well as a sufficient amount of tested specimens to ensure a statistically verified assessment, whereas a total number of four test data sets is analysed. Applying the recommended equivalent stress range approach and comparing the results with the design curves under CAL, it is shown that the use of the recommended value of the specified damage sum of $D = 0.5$ leads to a conservative fatigue assessment in all cases. Furthermore, an increased value of $D = 1.0$ still maintains a conservative design. Based on this work involving the analysed data sets, it can be concluded that the recommended procedure is well applicable and a conservative fatigue design is facilitated. As this study includes only a limited number of currently available data sets, a further validation considering additional VAL test data of HFMI-treated steel joints is scheduled in the future.

Acknowledgements Open access funding provided by Montanuniversität Leoben.

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