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Fatigue strength assessment of HFMI-treated steel joints under variable amplitude loading

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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 as well as elevated load stress 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 leads 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, 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]. In case of VAL, Palmgren [9] and Miner [10] proposed a linear damage accumulation, whereas a damage sum D of $D=0.5$ is conservatively recommended in [1, 7].
In [11], 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 analyzed data. In case of fluctuating mean stress states, even a lower damage sum of $D=0.2$ is investigated in [12], 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 Equ. 1.

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

Thereby, D is the specified damage sum, $\Delta\sigma_i$ is the stress range and k is the slope above the knee point of the S/N-curve, $\Delta\sigma_j$ is the stress range and k' 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 $k'=2 \cdot k-1$ [13] instead of the recommended [1] value of $k'=22$ applicable for CAL. Previously published studies [14-17] 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 Tab. 1, the VAL fatigue test data [18-20] 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 tension (and compression) loading at a load stress 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 parameter of $\nu=1$ and the Gaussian spectrum a value of $\nu=2.6$, see [21]. Further details in regard to fatigue testing under VAL are provided in [22].

Data set	Reference	Specimen type	Yield strength [MPa]	Plate thickn. [mm]	R-ratio [-]	Load spectrum
#1	[18]	Long. stiffener	355	5	0.1	Straight line
#2	[19]	Long. stiffener	S700	8	-1	Straight line
#3	[20]	Butt joint	S1100	6	0.1	Straight line
#4	[20]	Butt joint	S1100	6	0.1	Gaussian

Tab. 1: Overview of fatigue test data sets

Detailed information about the weld specimen geometries, mechanical properties of the base material, HFMI-treatment as well as the VAL testing procedure is given in each reference. In this study, the presented fatigue test data points of each reference is taken as basis for a further evaluation of the equivalent stress range and a final comparison to 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 an increased plate thickness or R-ratio, are needed to be taken into account. These further effects are validated in [8] 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 #1 are shown in Fig. 1 depicted with the maximum nominal stress range. The statistical analysis is performed by applying the standardized procedure given in [23] evaluating the S/N-curve at a survival probability of 97.7%. Tab. 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 fatigue strength range $\Delta\sigma$ is evaluated at this level accordingly.

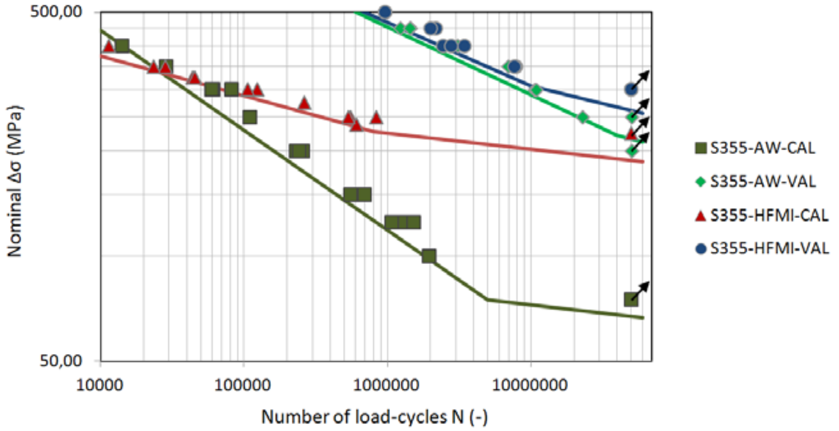

Fig. 1: Fatigue test results of data set #1 (maximum nominal stress range)

Test series	$\Delta\sigma$ (N=2e6) [MPa]	$\Delta\sigma$ (N=5e7) [MPa]	Slope m [-]	Scatter $1/T_\sigma$ [-]
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

Tab. 2: S/N-curve parameters of data set #1

The fatigue test results of data set #1 reveal a significant increase of the fatigue strength under CAL by a factor of about 2.8. In addition, the slope in the finite life regime increases from 3.5 to 5.2, which is in line with the recommended S/N-curves in the IIW-recommendations. 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 1.2 due to the post-treatment is observed. As presented in [18] and furthermore investigated in [24], 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 #2 are shown in Fig. 2 depicted with the maximum nominal stress range. Tab. 3 provides an overview of the statistically evaluated S/N-curve parameters. As the tests are conducted only within the finite life regime, the fatigue strength range $\Delta\sigma$ is evaluated 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 is observable. However, under VAL again a reduced benefit due to the post-treatment is investigated leading to an increase factor of about 1.3, whereas the tendency is in line with data set #1. The evaluated slopes again fit well to the recommended values.

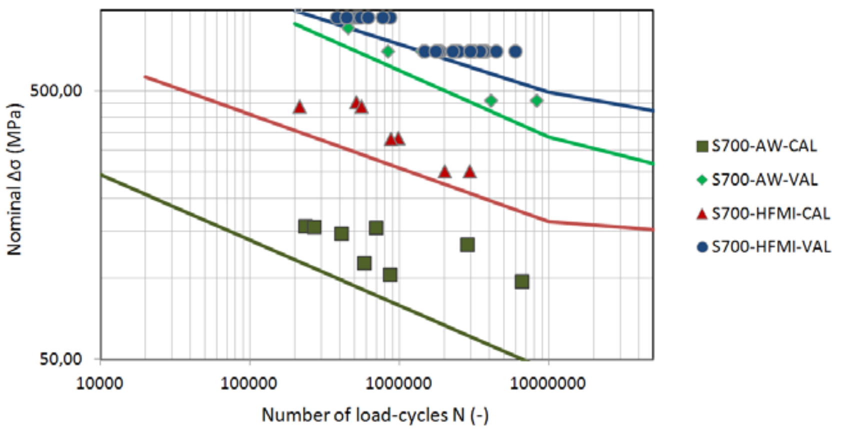

Fig. 2: Fatigue test results of data set #2 (maximum nominal stress range)

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

Tab. 3: S/N-curve parameters of data set #2

The fatigue test results of data set #3 are shown in Fig. 3, and the results of data set #4 are depicted in Fig. 4 depicted with the maximum nominal stress range. Tab. 4 and Tab. 5 provide an overview of the statistically evaluated S/N-curve parameters of the two data sets. As the tests are conducted up to a number of about thirty million load-cycles, the fatigue strength range Δσ is evaluated at this level accordingly. In case of the ultra-high strength butt joints, a different effect is observed. For both data sets involving two different load-spectra, the benefit by the HFMI-treatment is higher in case of VAL compared to CAL. In detail, under CAL an increase of a factor of about 1.2 for data set #3 and also for data #4 is observed. Under VAL, this factor elevates up to about 1.6 for data set #3 and about 2.0 for data set #4. In general, the benefit due to HFMI may be reduced for butt-joints exhibiting a comparably low stress concentration at the weld toe. In addition, it may be assumed that due to the use of the ultra high-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.

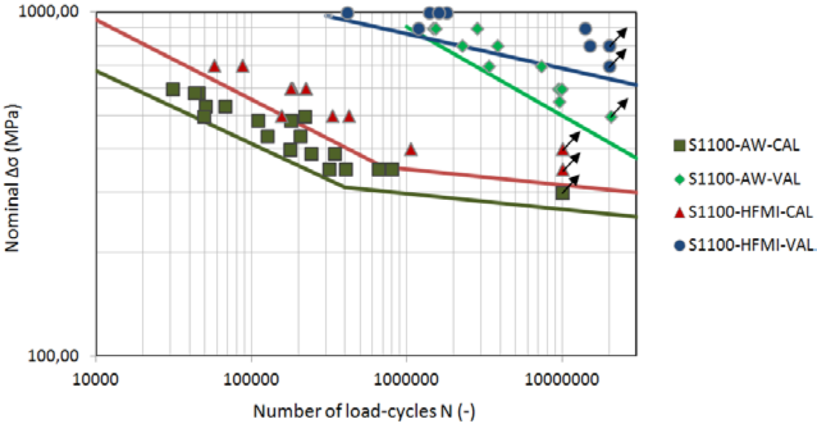

Fig. 3: Fatigue test results of data set #3 (maximum nominal stress range)

Test series	Δσ (N=2e6) [MPa]	Δσ (N=3e7) [MPa]	Slope m [-]	Scatter 1/Tσ [-]
S1100-AW-CAL	220	254	4.7	1.24
S1100-AW-VAL	757	377	3.9	1.22
S1100-HFMI-CAL	278	299	4.3	1.25
S1100-HFMI-VAL	808	615	9.9	1.25

Tab. 4: S/N-curve parameters of data set #3

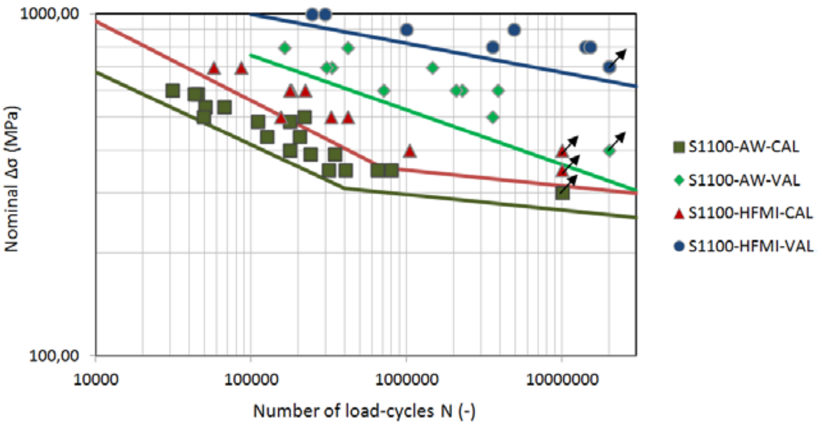

Fig. 4: Fatigue test results of data set #4 (maximum nominal stress range)

Test series	Δσ (N=2e6) [MPa]	Δσ (N=3e7) [MPa]	Slope m [-]	Scatter 1/Tσ [-]
S1100-AW-CAL	220	254	4.7	1.24
S1100-AW-VAL	470	305	6.3	1.30
S1100-HFMI-CAL	278	299	4.3	1.25
S1100-HFMI-VAL	774	614	11.6	1.18

Tab. 5: S/N-curve parameters of data set #4

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, Equ. 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 *k=5.0* and *k'=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 to the applicable design curve for the HFMI-treated joint under CAL.

Fig. 5 illustrates the results of the fatigue assessment of data set #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.

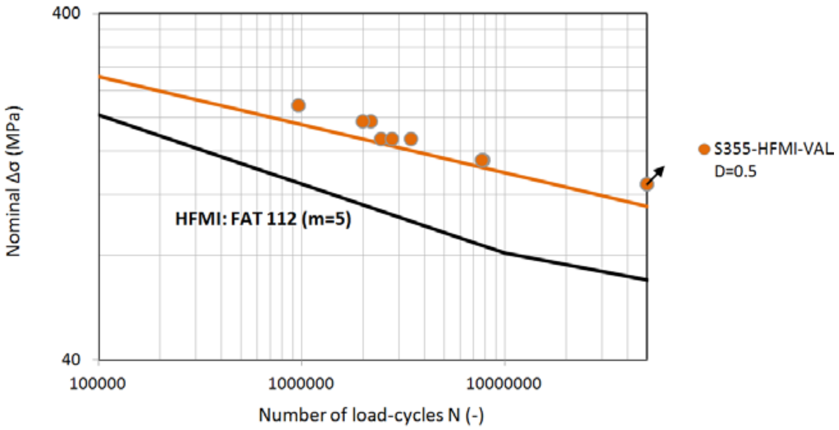

Fig. 5: Fatigue assessment of data set #1 (equivalent nominal stress range)
Specified damage sum *D=0.5*

Fig. 6 depicts the results of the fatigue assessment of data set #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 conservatively 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.

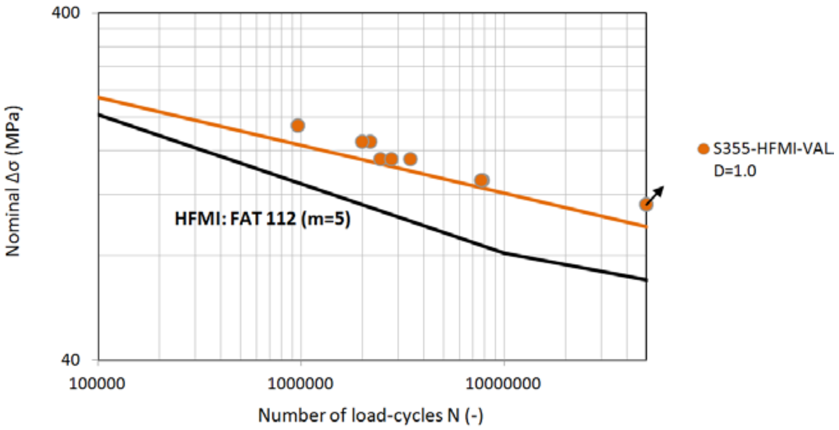

Fig. 6: Fatigue assessment of data set #1 (equivalent nominal stress range)
Specified damage sum *D=1.0*

Fig. 7 shows the results of the fatigue assessment of data set #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.

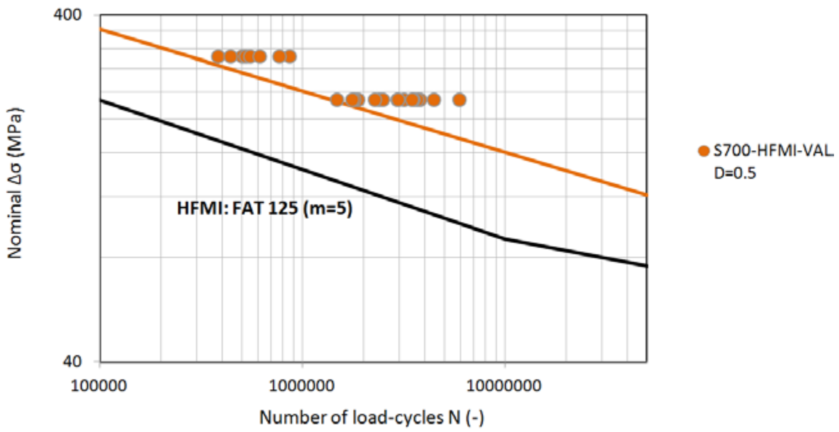

Fig. 7: Fatigue assessment of data set #2 (equivalent nominal stress range)
Specified damage sum *D=0.5*

Fig. 8 depicts the results of the fatigue assessment of data set #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.

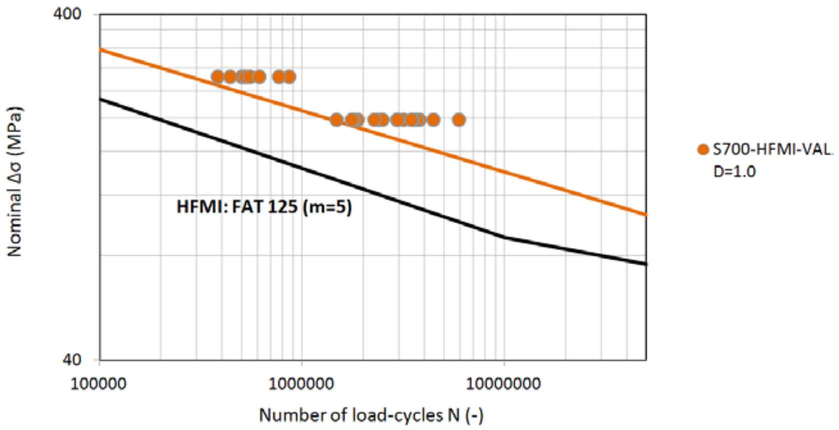

Fig. 8: Fatigue assessment of data set #2 (equivalent nominal stress range)
Specified damage sum *D=1.0*

Fig. 9 depicts the results of the fatigue assessment of data set #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.

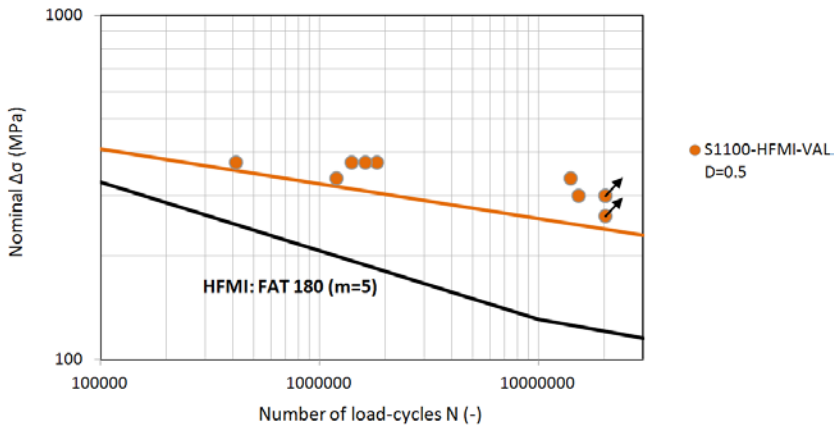

Fig. 9: Fatigue assessment of data set #3 (equivalent nominal stress range)
Specified damage sum *D=0.5*

Fig. 10 shows the results of the fatigue assessment of data set #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.

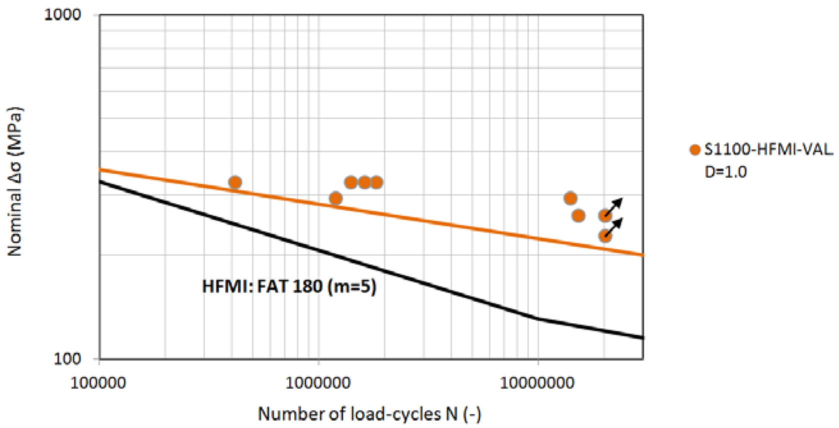

Fig. 10: Fatigue assessment of data set #3 (equivalent nominal stress range)
Specified damage sum *D=1.0*

Fig. 11 depicts the results of the fatigue assessment of data set #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.

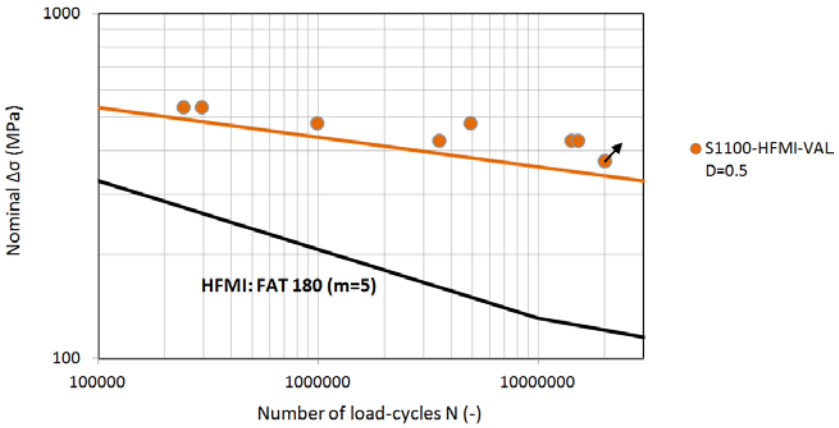

Fig. 11: Fatigue assessment of data set #4 (equivalent nominal stress range)
Specified damage sum *D=0.5*

Fig. 12 shows the results of the fatigue assessment of data set #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.

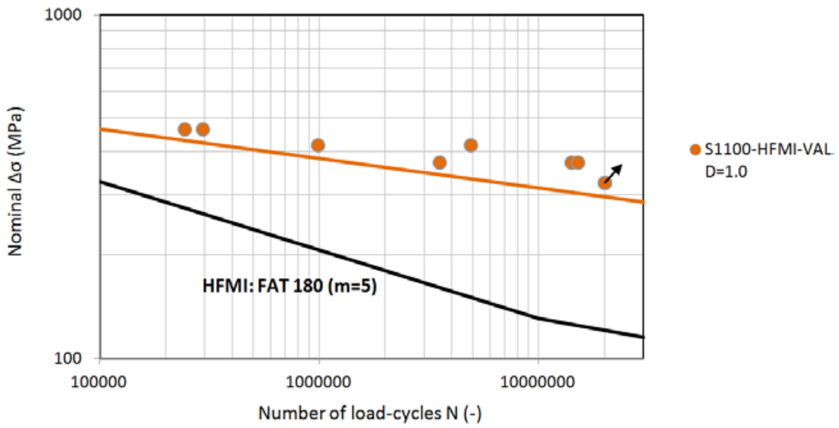

Fig. 12: Fatigue assessment of data set #4 (equivalent nominal stress range)
Specified damage sum *D=1.0*

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 [18], if not the recommended design curve under CAL is used as basis for the calculation, but an experimentally evaluated S/N-curve, the damage sum values may be reduced down to *D=0.2* in case of fluctuating mean stress states as given 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 to 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.

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