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Fatigue strength improvement factors for high strength steel welded joints treated by high frequency mechanical impact

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Abstract:

Numerous studies have observed that the fatigue strength of improved welds increases with material yield strength. This paper provides a comprehensive evaluation of published data for high frequency mechanical impact treated welds. In total, 228 experimental results for three weld geometries subject to R=0.1 axial loading have been reviewed. A design recommendation including one fatigue class increase in strength (about 12.5%) for every 200 MPa increase in static yield strength is proposed and are shown to be conservative with respect to all available data. Special cautions are given for high R-ratio or variable amplitude fatigue and potential alternate failure locations.

Keywords: high frequency mechanical impact (HFMI), weld toe improvement, fatigue strength improvement, high strength steel

Nomenclature

f_y	Yield strength
$f_{y,o}$	Reference yield strength
FAT	IIW fatigue class, i.e., the nominal stress range in MPa corresponding to 97.7% survival probability at $2 \cdot 10^6$ cycles to failure (a discrete variable with 10-15% increase in stress between steps)
k_o	Strength magnification factor for high frequency mechanical impact treatment for steel $f_y = f_{y,o}$
k_R	Strength magnification adjustment considering R-ratio
k_y	Strength magnification adjustment considering yield strength
m	Slope of the SN line
N_f	Cycles to failure
ΔS	Nominal stress range
ΔS^c	Yield strength corrected nominal stress range
ΔS^*	Fictitious nominal stress range for specimen *i* at $2 \cdot 10^6$ cycles to failure
X_N	Improvement factor in life for HFMI treated welds at ΔS equal to the FAT class of the as-welded joint: $N_f = X_N \cdot 2 \cdot 10^6$
α	Strength correction coefficient for yield after high frequency mechanical impact
γ	Strength correction coefficient for high frequency mechanical impact
σ_N	Standard deviation in Log (N_f)

subscripts

A	In the as-welded condition
K	Characteristic value corresponding to 97.7% survival probability at $2 \cdot 10^6$ cycles to failure (a continuous variable)
H	Following high frequency mechanical peening
i	value for specimen *i*
m	Mean value corresponding to 50% survival probability at $2 \cdot 10^6$ cycles to failure

1 INTRODUCTION

In 2007 the International Institute of Welding (IIW) Commission XIII on Fatigue of Welded Components and Structures approved the best practice guideline concerning post-weld treatment methods for steel and aluminium structures [**1**]. This guideline covers four commonly applied post weld treatment methods, burr-grinding, TIG re-melting (i.e. TIG dressing), hammer peening and needle peening. Burr-grinding and TIG re-melting are generally classified as geometry improvement techniques for which the primary aim is eliminate weld toe flaws and to reduce the local stress concentration by achieving a smooth transition between the plate and the weld face. Hammer peening and needle peening are classified as residual stress modification techniques which eliminate the high tensile residual stress in the weld toe region and induce compressive residual stresses at the weld toe. These methods also result in a reduced stress concentration at the weld toe. The guideline also gives practical information on how to implement the four improvement technologies including good work practices, training, safety, and quality assurance.

The IIW guideline for post-weld improvement applies to plate thickness 6 to 50 mm for steel and 4 to 20 mm for aluminium. The improvement methods are only relevant to fatigue failures initiating from the weld toe. Thus, in some situations alternate failure modes must also be considered. For welds improved by burr grinding or TIG re-melting or for hammer peening or needle peening of low strength steel (f_y < 355 MPa), the fatigue strength benefit corresponds to an increase in allowable stress range by a factor of 1.3, corresponding to a factor of 2.2 on life (for SN slope m = 3). However, the maximum class which can be claimed is the closest category below the FAT value obtained when the as-welded FAT value is multiplied by 1.3. For ease of computation, this corresponds to a two (2) fatigue class increase based on the IIW Fatigue Design Recommendations [**2**].

For higher strength steel (f_y > 355 MPa) welds improved by hammer peening or needle peening, the fatigue strength benefit consists of an upgrade by a factor of 1.5 applied to the stress range. For ease of computation, this corresponds to a three (3) fatigue class increase. For example, when a weld detail which, in the as-welded condition, would be classified as FAT 63 is hammer peened, the new FAT value is FAT 90. The highest detail class for which an improvement can be claimed is FAT 90, and the highest SN curve that can be claimed following improvement is FAT 125. The slopes of the SN curves follow the IIW Fatigue Design Recommendations [**2**].

An important practical limitation on the use of peening improvement techniques that rely on the presence of compressive residual stresses is that the fatigue lives are strongly dependent on the applied mean stress. In particular, the degree of improvement decreases as the maximum applied stress approaches tensile yield. Thus, in general, the techniques are not suitable for structures operating at applied stress ratios R > 0.5 or maximum applied stresses above around 80% yield. The guideline gives special limitations for high stress ratio situations. Even occasional application of high stresses in tension or compression as part of a variable amplitude fatigue history, can also be detrimental in terms of relaxing the compressive residual stress. Systematic guidelines are not yet developed. Special limitations also exist for improved large-scale structures. It is recommended that for steel structures with plate thickness greater than 20 mm the benefit for hammer peening is assumed to be the same as for burr grinding and TIG dressing. Burr grinding and TIG re-melting can be applied only to conditions where $\Delta S < 2f_y$.

The original technology for high frequency mechanical impact (HFMI) was developed at the Northern Scientific and Technological Foundation in Russia in association with Paton Welding Institute in the Ukraine [**3**]. The past decade has seen steady increase in the number of HFMI peening equipment manufacturers and service providers. Numerous power sources are employed, e.g., ultrasonic piezoelectric elements, ultrasonic magnetostrictive elements or compressed air. In all cases, however, the working principal is identical: cylindrical indenters are accelerated against a component or structure with high frequency. The impacted material is highly plastically deformed causing changes in the material microstructure, the local geometry and the residual stress state in the region of impact. In comparison to hammer peening, the operation is more user-friendly and the spacing between alternate impacts on the work piece is very small resulting in a finer surface finish. The indenters are high strength steel cylinders and manufacturers have customized the effectiveness of their own tools by using indenters with different diameters, tip geometries or multiple indenter configurations. Devices are known by the names: ultrasonic impact treatment (UIT) [**4**], ultrasonic peening (UP) [**5**], ultrasonic peening treatment (UPT) [**6**] [**7**], high frequency impact treatment (HiFiT) [**8**], pneumatic impact treatment (PIT) [**9**] and ultrasonic needle peening (UNP) [**10**] [**11**].

Yildirim and Marquis [**12**] have published a comprehensive review of experimental data on the fatigue strength of welded joints improved by HFMI peening methods. Most of the nearly 400 reported tests were performed using constant amplitude R=0.1 axial tension fatigue, but some data for other R-ratios, variable amplitude testing and bending fatigue are also reported. Material yield strength varied from 260 MPa to 960 MPa. The extracted fatigue test data was statistically analysed in order to estimate the best slope for the SN line and to investigate the degree of improvement for each specimen type. They found that an SN slope of m=5 fits both the available HFMI treated fatigue data and the existing data for hammer peened welds. Thus, all of the following conclusions are based on an assumed SN slope of m=5 and fatigue strength improvements are defined at $N=2\cdot10^6$.

Numerous researchers have observed that the degree of improvement for post-weld treated components increases with material strength, see, e.g., Maddox [**13**], Bignonnet [**14**], Haagensen [**15**] , Weich [**16**] and Yildirim and Marquis [**12**]. However, the IIW best practice guideline concerning post-weld treatment methods for steel and aluminium structures [**1**] makes only a single division between low strength and high strength steel at f_y = 355 MPa. This single division was primarily due to the lack of systematic experimental data for higher strength steels. In order to stimulate research on higher strength steels, IIW Commission XIII initiated a round robin exercise in 2003. Results of this exercise in combination with numerous other studies have now been completed and conclusions concerning the relationship between yield strength and fatigue strength can be made. The current study specifically considers only welds improved using HFMI treatment tested at constant amplitude R=0.1. No attempt is made to make distinctions between the previously mentioned technologies. Observations on high stress ratio fatigue or variable amplitude fatigue made in the IIW guideline should still be considered as valid.

As a result of several research projects in Germany, Weich [**16**] has proposed a design method for HFMI treated welds. In this proposal, the SN curve slope should be m=5. The characteristic fatigue strength following HFMI treatment is

$$\Delta S_H = \Delta S_A \cdot (k_o \cdot k_y \cdot k_R) \quad (1)$$

where the strength magnification factors are given by Eq. (2).

$$k_o = \gamma \quad (2a)$$

$$k_y = 1 + \alpha\,(1 - f_{y,0} / f_y) \text{ for } f_y \leq 690 \text{ MPa} \quad (2b)$$

$$k_R = 1.0 \text{ for } R < 0.1 \quad (2c)$$

$$k_R = 1.075 – 0.75R \text{ for } 0.1 \le R \le 0.5$$

Values $f_{y,o}$ = 355 MPa, γ = 1.6 and α = 0.6 were proposed.

2 METHODS

2.1 Published Data

In a review of published experimental data on the fatigue strength of welded joints improved by HFMI peening methods, Yildirim and Marquis [**12**] identified 19 publications containing fatigue data for welded steel joints improved by one of the HFMI methods mentioned in the introduction. Some of these studies contained multiple materials, improvement techniques, stress conditions or specimen types. Thus, a total of 46 data sets for four specimen types were reviewed.

In the current study, only data for axially loaded test specimens loaded at R=0.1 loading were analysed. It has been observed that a variety of alternate failure modes are observed for HFMI treated welds depending on the type of fatigue loading [**17**]. Wherever possible, failure modes other than at the weld toe and run-outs have been excluded. The yield stress of steel grades varies from 260 to 969 MPa, and specimen thickness varies from 5 to 30 mm. The 228 data points from 24 data sets analysed in the current study are summarized in Tables 1-3. These tables show the specimen type, thickness, f_y, HFMI method, and number of test specimens for each data set. In cases where f_y was not specifically reported, values were taken from published datasheets [**18**] [**19**] [**20**]. The FAT class of each specimen type is taken from the IIW Recommendation [**2**] and ΔS_m are typical values from IIW recommendations [**21**]. These are presented in Table 4.

2.2 Data Assessment

Several different hypotheses were investigated as a mean of establishing the empirical relationship between yield strength and fatigue strength for HFMI treated welds. Even though Eq. (2b) was originally limited to $f_y \le 690$ MPa, the form of the equation was evaluated also to include yield strengths up to 960 MPa. Values of γ and α were systematically changed to determine which values would result in minimum σ_N for the data. Additionally, a strength magnification factor which increases linearly with yield strength, Eq. (3), was used with a product form, Eq. (4) and an exponential form Eq. (5). When assessing the data, it was assumed that 1) the slope of SN curves for HFMI improved welds was *m*=5, 2) that fatigue strength values from Table 4 are valid and 3) the best fit for the data resulted in minimum σ_N. In the current study only data for R = 0.1 was evaluated and no statement can yet be made concerning stress ratio, Eq, (2c).

$$k_y = \alpha \, (f_y - f_{y,o})/ f_{y,o} \quad (3)$$

$$\Delta S_H = \Delta S_A \cdot k_o \cdot (1+ k_y) \quad (4)$$

$$\Delta S_H = \Delta S_A \cdot (k_o)^{1/(1- k_y)} \quad (5)$$

While all of the proposed equations resulted in a reduction in σ_N with respect to the data with no yield strength compensation, the best fit for the data was found using Eq. (5) with k_y defined by Eq. (3).

For a single fatigue test result for a HFMI treated specimen tested at ΔS_i and with fatigue life $N_{f,i}$, the fictitious nominal stress range at $N_f = 2\cdot10^6$ was computed using Eq. (6) with *m*=5.

$$\Delta S_i^* = ((\Delta S_i)^m \cdot N_{f,i} / 2{\cdot}10^6)^{1/m} \quad (6)$$

For evaluating test data, the mean fatigue strength from Table 4, ΔS_m, for a particular weld joint type was used. Based on Eq. (5), the yield strength corrected nominal stress range for specimen *i* at $2{\cdot}10^6$ cycles to failure, ΔS_i^c is given by Eq. (7). With Eq. (7) k_y was defined as in Eq. (3) and $f_{y,0}$ = 355 MPa.

$$\Delta S_i^c = (\Delta S_{m,A})^{k_y} \cdot (\Delta S_i^*)^{1-k_y} \quad (7)$$

3 RESULTS

The best fit to the data was found using Eq. (3) with Eq. (5). Parameter α was adjusted so as to minimize σ_N. Regression analysis with a forced slope m=5 was used to analyse the published HFMI data from Tables 1-3 to determine ΔS_m and ΔS_k. For each specimen type, the value α reported in Table 5 is that value which produced minimum σ_N. The table also shows the data without f_y correction, i.e., ΔS and N_f values reported in the individual studies were used without adjustment. The f_y corrected and un-corrected data are shown graphically in Figures 1-3.

In order to evaluate all three specimen types as a single data set, fatigue strength values were normalized by dividing both sides of Eq. (7) by $\Delta S_{m,A}$ from Table 4 for the appropriate joint geometry.

$$(\Delta S_i^c / \Delta S_{m,A}) = (\Delta S_i^* / \Delta S_{m,A})^{1-k_y} \quad (8)$$

When evaluated as a single data set based on Eq. (8), the minimum σ_N was found for α = 0.27. The resulting normalized mean and characteristic fatigue strength values are 1.69 and 1.32, respectively. These are given numerically in Table 5 and data for all geometries presented as a single data set is shown graphically in Fig. 4.

4 DISCUSSION

4.1 Evaluation of the f_y correction factor

Equation 5 was derived based on an assumption HFMI treatment of welded joints fabricated from steel with f_y = 355 MPa have a fatigue strength $\Delta S_A \cdot (k_o)$ at $N_f = 2{\cdot}10^6$ and that Log(ΔS) increases linearly with f_y for $f_y > f_{y,0}$. Other functions could have been assumed in place of, Eq. (3), but the natural scatter in the data would make it difficult to justify more complicated expressions. Table 5 clearly shows that the use of f_y correction results in decreased σ_N and lower ΔS_k and ΔS_m for each specimen type. Lower values of ΔS_k and ΔS_m are to be expected since these values represent the lines for HFMI treated specimens at the reference f_y = 355 MPa. Without correction (α = 0) the curves are higher since the lines represent a mix of test specimens with a wide variety of yield strengths. While ΔS_m reduces by 6-16% for the three specimen types, ΔS_k changes by less than 3% due to the significant reduction in σ_N. From Tables 4 and 5 it is interesting to note that, for each specimen type, σ_N for HFMI treated welds with f_y correction is less than σ_N expected for specimens in the as-welded condition.

Between specimen types, there is a small difference in the value of α which results in a minimum value for σ_N. The greatest value of α = 0.39 was observed for transverse welds while the lowest was observed for the longitudinal attachments, α = 0.23. When all experimental results are evaluated as a single data set the value $\alpha = 0.27$ is found. However, it can be noted that σ_N changes only slowly with α. In practice, the value $\alpha = 0.27$ means that ΔS_m increases by about 10% for every 200 MPa increase in f_y above the reference value of 355 MPa. In the IIW system this is approximately equal to one fatigue class for every 200 MPa increase in f_y. It also indicates a similar decrease in ΔS_m for $f_y < 355$ MPa.

Figure 5 shows a proposed increase in number of FAT classes as a function of yield strength. The solid line presents the proposed increase and the broken line represents the increase for hammer and needle peened welds in the current IIW guideline [**1**]. Table 6 presents the existing IIW recommended FAT classes for the three joint geometries evaluated in this study in the as-welded condition and followed by hammer or needle peening. The table also shows the proposed FAT classes for HFMI treated joints as a function of f_y.

In the high cycle regime, the proposed increase in fatigue strength for HFMI treated high strength steel welds can be significantly greater than that proposed in the IIW guideline for hammer or needle peened welds. In the low and medium cycle regime, however, the new proposal may even result in lower allowable stresses. With reference to Fig. 5 and Table 6, for longitudinal welds with $355 < f_y \leq 550$ MPa, the current study shows a maximum FAT class increase of five (5) while the IIW guideline gives only three (3). It should be noted, however, that the current study is based on a recommended SN slope m=5 while the IIW guideline uses m=3. This means that for $N_f < 3.7 \cdot 10^5$ cycles, the current proposal actually allows *lower* ΔS in comparison with the IIW guideline even though the current study proposes an increase of two additional FAT classes. For longitudinal welds with $550 < f_y \leq 750$ MPa, the current study proposes a FAT class increase of six (6). This means that the current proposal allows lower ΔS than the IIW guideline for $N_f < 1.8 \cdot 10^5$ cycles. Even for the greatest yield strength $f_y > 950$ MPa, the current study proposes an increase of eight (8) FAT classes. In this case the current proposal allows lower ΔS than the IIW guideline for $N_f < 2.4 \cdot 10^4$ cycles. Similar observations can be made for the other joint geometries.

Based on the proposed FAT classes in Table 6, the HFMI experimental data for longitudinal, transverse and butt welds fabricated from different strength steels are plotted in Figs. 6-8. With the exception of one single data point in Fig 8a, the proposed FAT lines are conservative with respect to the experimental data. The design FAT lines are intended to represent 97.7% survival probability so one point, or even several points, in 228 below the lines should be expected. If needed, greater survival probability lines can easily be computed based on the σ_N values reported in Table 5. Table 6 shows that butt welds with $f_y > 550$ MPa, transverse welds with $f_y > 750$ MPa and longitudinal welds with $f_y > 950$ MPa have a proposed FAT class of 180 with m=5. This value is higher than the IIW Recommendation for plate edges for all grades of steel (FAT class of 160 with m=5). Plate edges can be treated so as to improve the fatigue strength [**22**], so FAT greater than 180 MPa is possible. However, this raises the general issue of failure starting at some other location in a structure. Such possibilities must always be considered. For instance, if the failure origin is merely shifted from the weld toe to a near-by start-stop position or to the weld root, there may be no significant improvement in fatigue strength. Improvement of details with incomplete penetration should be verified by fatigue testing or by analysis [**23**]. Consequently, when weld improvement is planned, full penetration welds or welds with extra-large throats should be used in regions of high stress.

The selection of an SN slope m=3 in the IIW guideline [**1**] was partially due to the convenience of having SN lines for improved welds which are parallel to the lines for welds in the as-welded condition. This results in a constant improvement in N_f for all ΔS. The current proposal for HFMI treated welds includes m=5 which produces a variable improvement in N_f with ΔS. Table 7 shows the computed increase in the fatigue life for joints improved by hammer or needle peening or HFMI. The improvement is given as multiplication factor, X_N, in fatigue life for a joint subjected to ΔS equivalent to the FAT class. Thus, in the as-welded condition, the design life is $N_f = 2 \cdot 10^6$ and the expected design life is for a joint improved by hammer or needle peening or HFMI is $N_f = X_N \cdot 2 \cdot 10^6$. For joints improved by hammer or needle peening, X_N according to the IIW guideline is approximately 2 for $f_y \leq 355$ and 2.7 for $f_y > 355$. In the current proposal the values of X_N are only valid for a single ΔS which in this case is chosen to be equal to the FAT class for the joint in the as-welded condition. For higher ΔS the values of X_N would need to be reduced. The dramatic increase in X_N as a function of f_y is clearly visible in Table 7. For example, for longitudinal attachments the value of X_N increases from 9.8 for $f_y \leq 355$ to more than 100 for $950 < f_y$.

4.2 Caution concerning R-ratio and variable amplitude loading

Virtually all the published data for HFMI treated welds involved R=0.1 constant amplitude loading. Recently, however, an increasing number of studies have also used higher R-ratio testing or variable amplitude testing [**24**] [**25**] [**26**] [**27**] [**28**] [**29**] . Several studies including large scale component testing are also in progress or are recently completed [**30**]. A new guidance document covering HFMI can only be completed once this data is available. For needle or hammer peening, the fatigue strength improvement benefit is known to be sensitive to R-ratio. Similar observations have been made for HFMI treated welds [**29**] [**25**]. In the IIW guideline for needle or hammer peening, for example, the fatigue strength benefit is fully realized for $R \leq 0.15$. For $R > 0.15$, the expected fatigue strength improvement is less. For example, $0.15 < R \leq 0.28$ results in one FAT class less benefit while $0.28 < R \leq 0.4$ results in a two (2) FAT class reduction. For $R > 0.4$, no fatigue strength improvement can be claimed without testing. Proper R-ratio limits for high strength steels need to be determined based on experiments and relevant modelling.

For variable amplitude loading the IIW Recommendations use a SN line that changes slope from m for $N < 1 \cdot 10^7$ to $(2m\text{-}1)$ for $N > 1 \cdot 10^7$. This damage hypothesis has not been verified for HFMI treated welds. Marquis [**17**] has observed that the failure modes for specimens tested using variable amplitude loading can be different than for identical specimens tested using constant amplitude. During VA loading the local stresses at the improved weld toes during large cycles may be sufficiently high that reversed local yielding is expected and the beneficial compressive residual stresses are probably reduced. For most service conditions the effectiveness of post weld improvement techniques should be assessed using suitable VA loading since CA may give over-optimistic conclusions concerning the degree of improvement expected. This is a significant area where further research is welcome.

5 CONCLUSIONS

This paper provides a comprehensive evaluation of published data for high frequency mechanical impact treated welds subject to R=0.1 constant amplitude loading. In total 228 experimental results for longitudinal, transverse and butt welds subject to axial loading have been reviewed. An increase in fatigue strength with yield strength was found. By choosing $f_{y,o} = 355$ MPa as a reference, approximately 12.5% increase in strength for every 200 MPa increase in f_y above $f_{y,o}$ was found. This correction significantly reduced the observed scatter in the data with respect to data without any yield strength correction. This value of was adopted as a basis for proposing design curves for high frequency mechanical impact treated welds. The proposed SN lines are conservative with respect to available data. Special cautions are given for high R-ratio or variable amplitude fatigue and alternate failure locations.

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19. SSAB: Domex 700 MC Hot rolled, extra high strength, cold forming steel., DATA SHEET: 11-02-03 GB8421 DOMEX.

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Table 1. Experimental R=0.1 constant amplitude axial fatigue data for HFMI treated longitudinal welds.

Ref.	steel type	f_y (MPa)	treatment method	plate thickness (mm)	number of specimens in series
[**31**]	S700	700[2]	UP/ UIT	8	16
[**25**]	S690QL	786[1]	UIT	16	16
[**25**]	S690QL	786[1]	HiFIT	16	15
[**32**]	16Mn	390[2]	UP/UPT	8	6
[**33**]	S350	398[1]	UP/UPT	12	5
[**33**]	S700	780[1]	UP/UPT	12	7
[**33**]	S900	900[1]	TIG+UP	12	10
[**34**]	SS800	700[1]	UP/UPT	8	8
[**34**]	16Mn	390[1]	UP/UPT	8	6
[**34**]	Q235B	267[1]	UP/UPT	8	7
[**35**]	S355	355[2]	UIT	8	10

[1] measured f_y
[2] nominal f_y

Table 2. Experimental R=0.1 constant amplitude axial fatigue data for HFMI treated cruciform welds.

Ref.	steel type	f_y (MPa)	treatment method	plate thickness (mm)	number of specimens in series
[**24**]	S355J2	398[1]	UIT	12	7
[**24**]	S355J2	398[1]	UIT	12	4
[**24**]	S460ML	504[1]	UIT	12	5
[**24**]	S460ML	504[1]	UIT	12	5
[**36**]	S260	260[2]	UIT	20	9
[**37**]	S355J2	477[1]	PIT	12	8
[**37**]	S690QL	781[1]	PIT	12	7
[**26**]	AH36	392[1]	UIT	20	3
[**26**]	AH36	392[1]	UIT	20	3

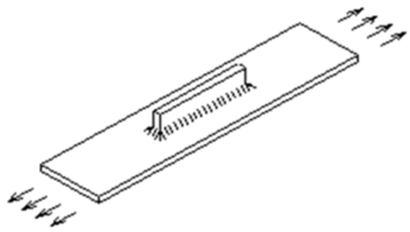
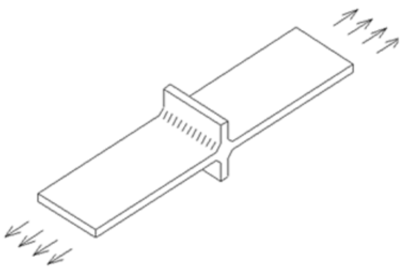
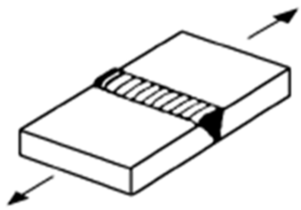
[1] measured f_y
[2] nominal f_y

Table 3. Experimental R=0.1 constant amplitude axial fatigue data for HFMI treated butt welds.

Ref.	steel type	f_y (MPa)	treatment method	plate thickness (mm)	number of specimens in series
[**25**]	S355J2	422[1]	UIT	16	14
[**25**]	S355J2	422[1]	HiFIT	16	18
[**25**]	S690QL	786[1]	UIT	16	18
[**25**]	S690QL	786[1]	HiFIT	16	12
[**38**]	E690	763[1]	UP	9.5	8
[**39**]	S960	960[2]	PIT	5	7

[1] measured f_y
[2] nominal f_y

Table 4. FAT values for welded joints evaluated in this study

Specimen Type	FAT (MPa) [**2**]	$\Delta S_{m,A}$ (MPa)	σ_N [**21**][2]	
Longitudinal attachment	71[1]	97	0.206	
Cruciform joint	80	110	0.206	
Butt joint	90	123	0.206	

[1]Note that FAT 71 is for 50 < *l* < 150 mm (*l* = attachment length). Larger or smaller FAT values are seen as *l* changes. For simplicity FAT 71 was assumed for all longitudinal attachments.

[2]Typical values used by the International Institute of Welding

Table 5. Statistical analyses of published data from Tables 1-3. Each specimen type is analysed with f_y correction (Eq. (5) and Eq. (7), $\alpha > 0$) and without f_y correction ($\alpha = 0$). SN slope $m = 5$ was assumed.

Specimen Type	total data points	α	ΔS_k (MPa)	ΔS_m (MPa)	σ_N
Longitudinal attachment	116	0	134	196	0.415
		0.23	129	170	0.302
Cruciform joint	39	0	164	218	0.307
		0.31	166	204	0.156
Butt joint	73	0	170	242	0.381
		0.39	168	204	0.213
All joints	218	0.27	normalized values		0.274
			1.32	1.69	

Table 6. Existing IIW FAT classes for as-welded and hammer or needle peened welded joints and the proposed FAT classes for HFMI treated joints as a function of f_y.

f_y (MPa)	longitudinal welds	transverse welds	butt welds
		as-welded, m = 3 [**2**]	
all f_y	71	80	90
		improved by hammer or needle peening, m = 3 [**1**]	
$f_y \le 355$	90	100	112
$355 < f_y$	100	112	125
		improved by HFMI, m = 5	
$235 < f_y \le 355$	112	125*	140*
$355 < f_y \le 550$	125	140	160
$550 < f_y \le 750$	140	160	180
$750 < f_y \le 950$	160	180*	-
$950 < f_y$	180	-	-

* no data available

Table 7. Computed X_N factors for joints improved by hammer or needle peening or HFMI and subjected to ΔS equivalent to the FAT class. Thus, the expected design life is for a joint improved by hammer or needle peening or HFMI is $X_N \cdot 2 \cdot 10^6$.

f_y (MPa)	longitudinal welds (ΔS = 71 MPa)	transverse welds (ΔS = 80 MPa)	butt welds (ΔS = 90 MPa)
	X_N factors for joints improved by hammer or needle peening, *m* =3 [**1**]		
$f_y \leq 355$	2.0	2.0	1.9
$355 < f_y$	2.8	2.7	2.7
	X_N factors for joints improved by HFMI, *m*=5		
$235 < f_y \leq 355$	9.8	9.3	9.1
$355 < f_y \leq 550$	16.9	16.4	17.8
$550 < f_y \leq 750$	29.8	32.0	32.0
$750 < f_y \leq 950$	58.1	57.7	-
$950 < f_y$	104.7	-	-

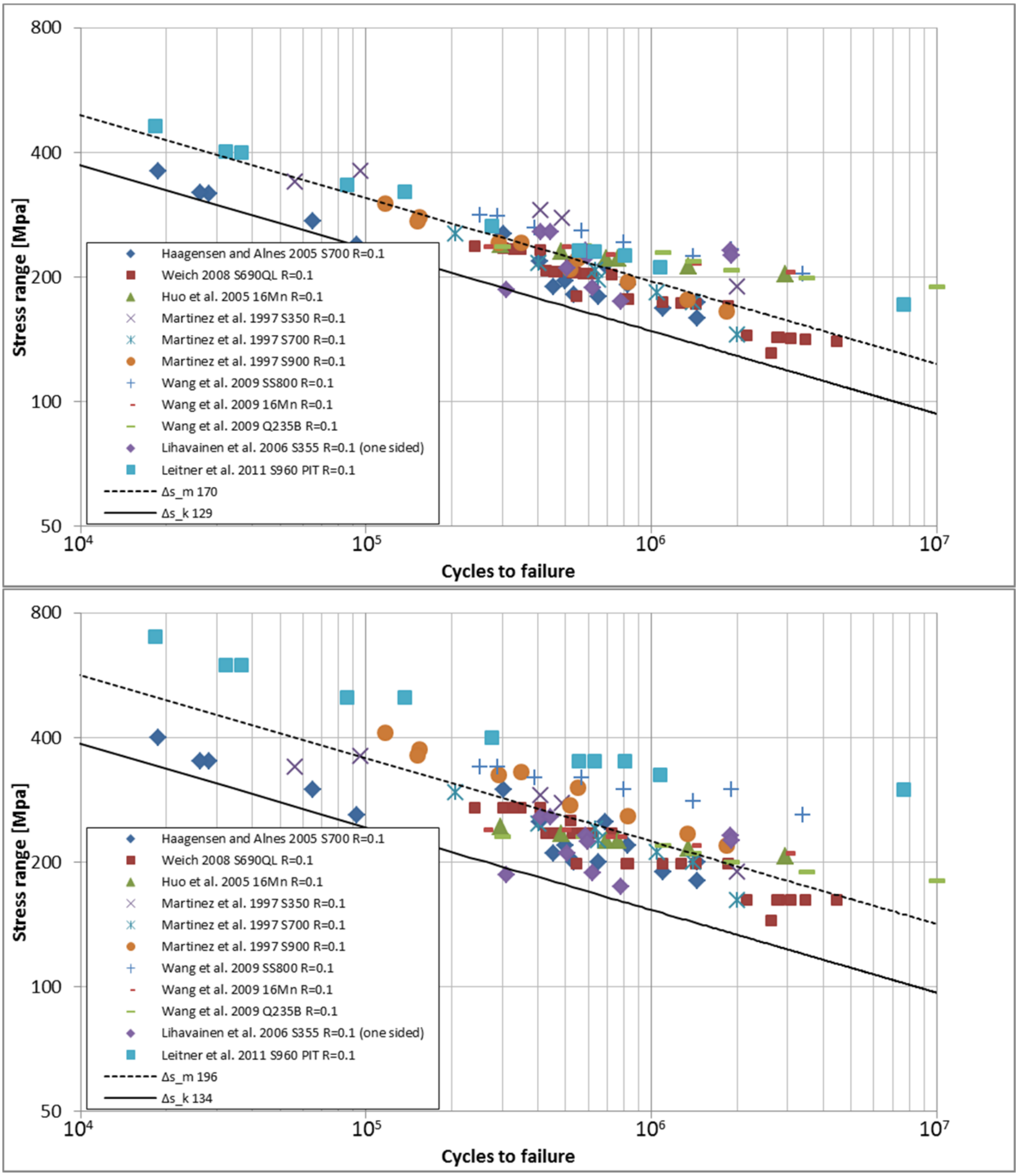


Figure 1. Fatigue data for improved longitudinal welds with f_y correction, α = 0.23 (upper) and without f_y correction (lower)

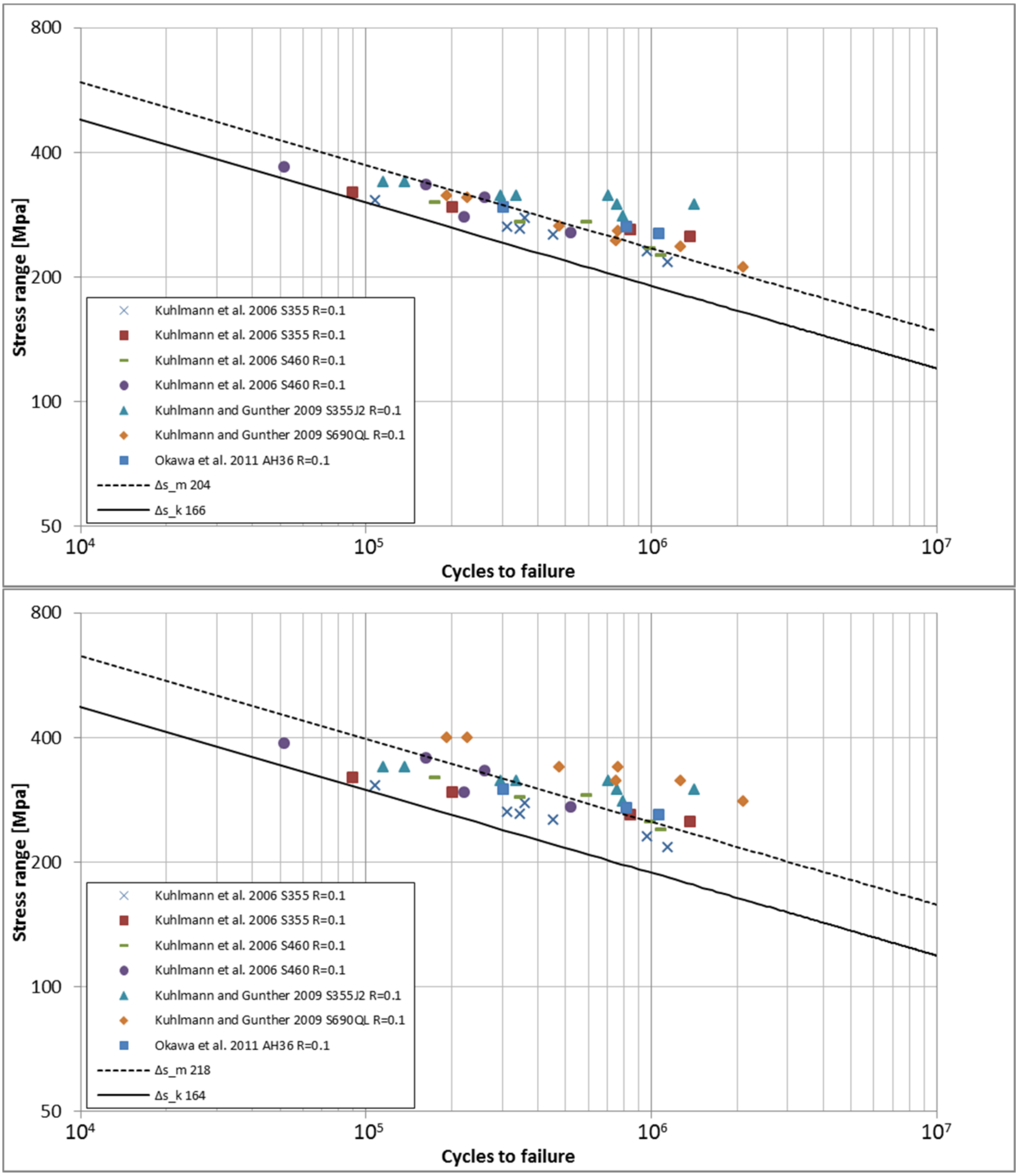


Figure 2. Fatigue data for improved cruciform welds with f_y correction, α = 0.31 (upper) and without f_y correction (lower)

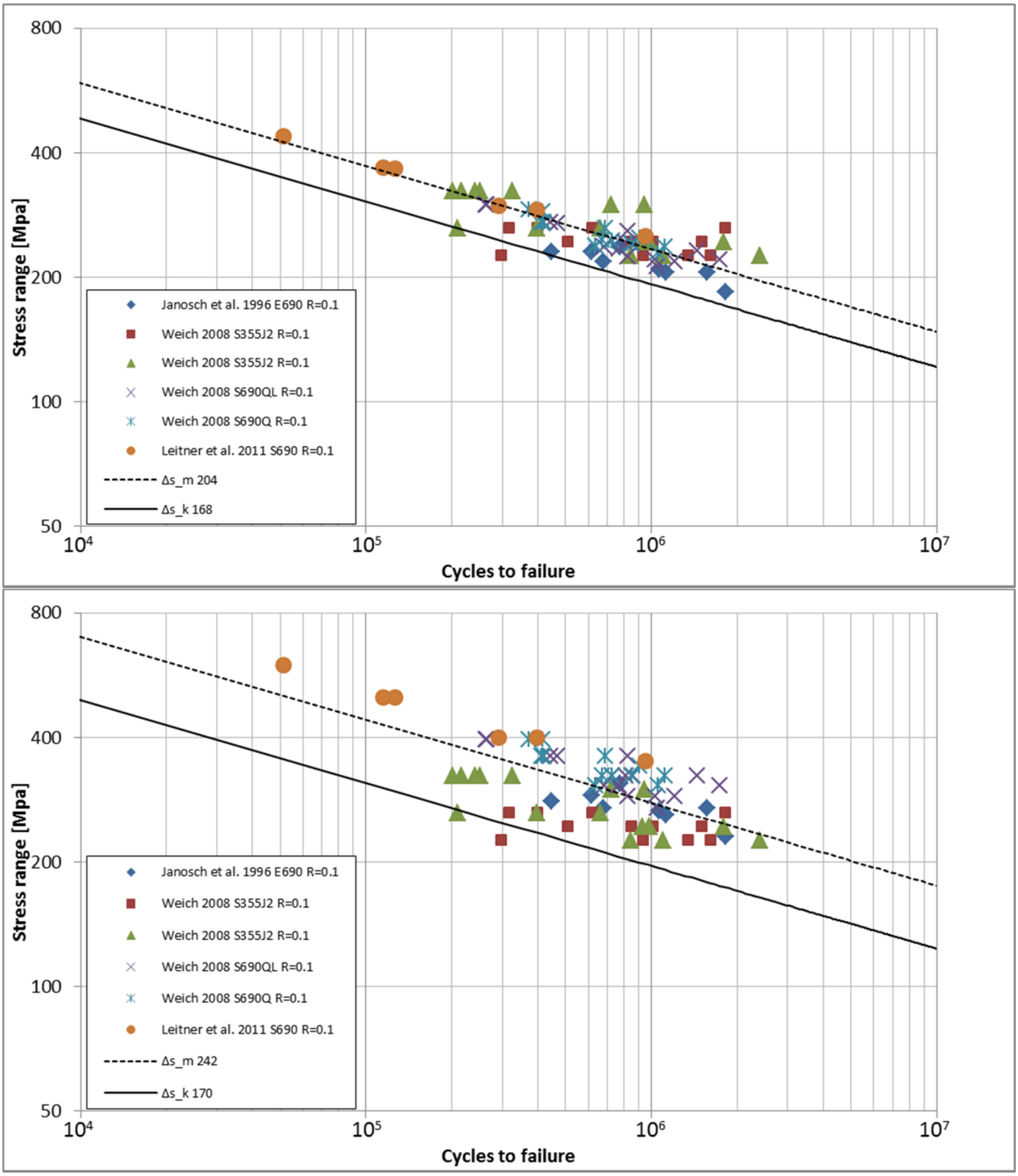


Figure 3. Fatigue data for improved butt welds with f_y correction, $\alpha = 0.39$ (upper) and without f_y correction (lower)

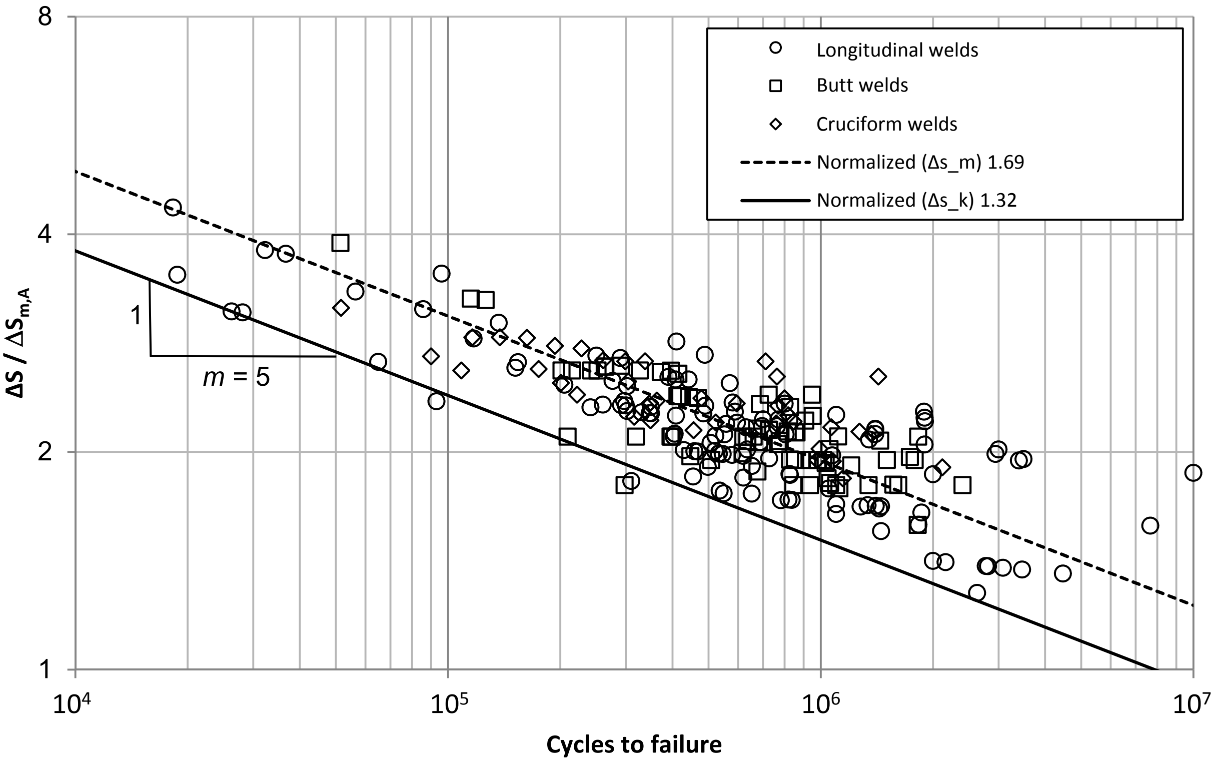


Figure 4. Normalized fatigue data for all three joint geometries based on Eq. (8) with $\alpha = 0.27$.

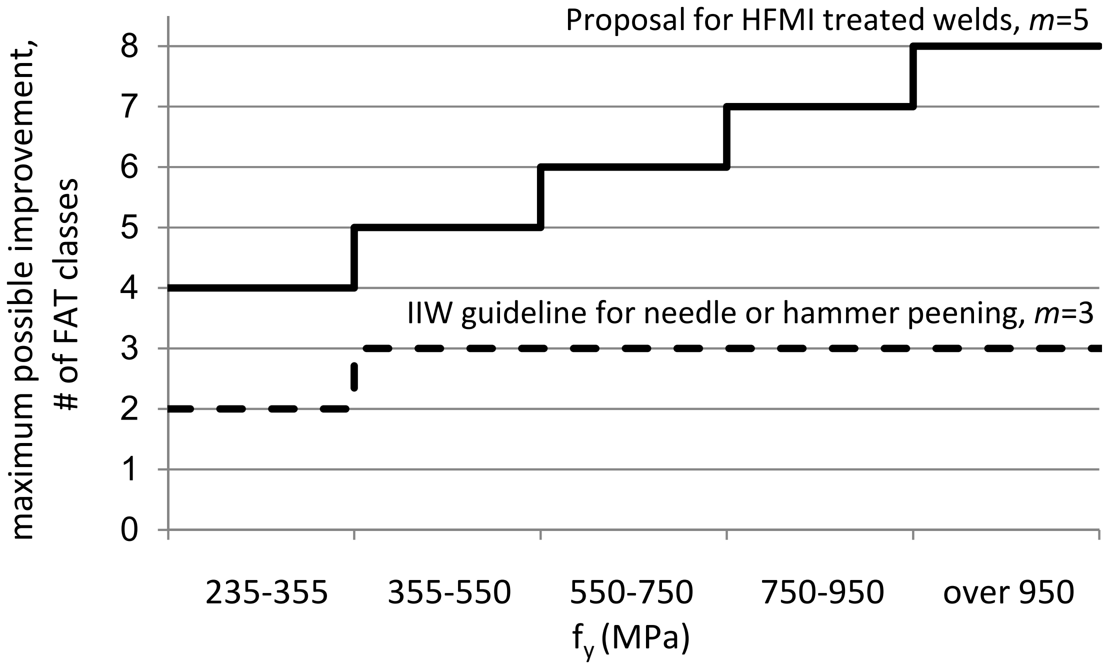


Figure 5. Proposed maximum increase in the number of FAT classes as a function of f_y

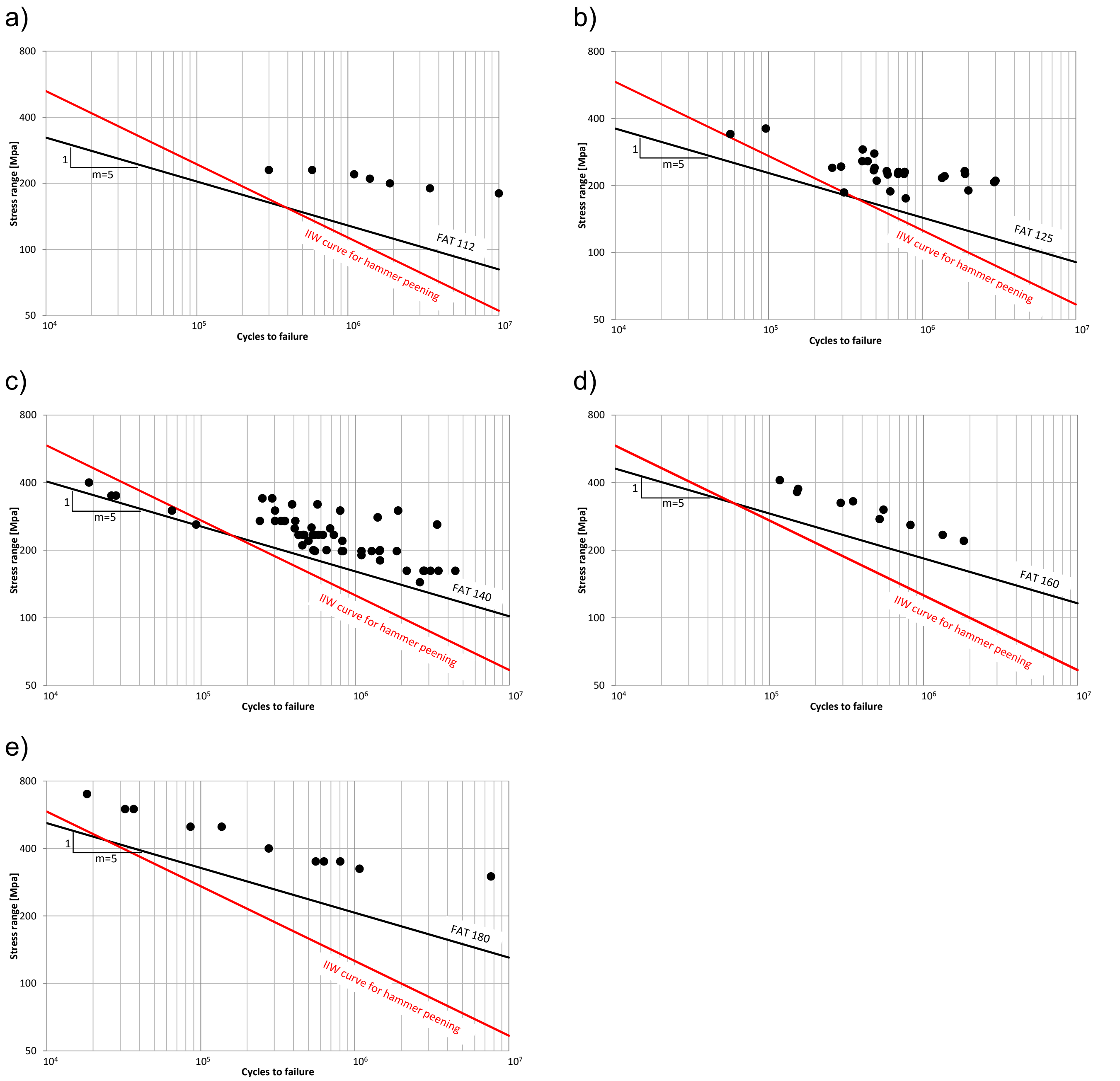


Figure 6. Available data for HFMI treated longitudinal welds shown in relation to the design curves proposed in Table 6: a) 235 < f_y ≤ 355 b) 355 < f_y ≤ 550 c) 550 < f_y ≤ 750 d) 750 < f_y ≤ 950 and e) 950 < f_y

a) b)

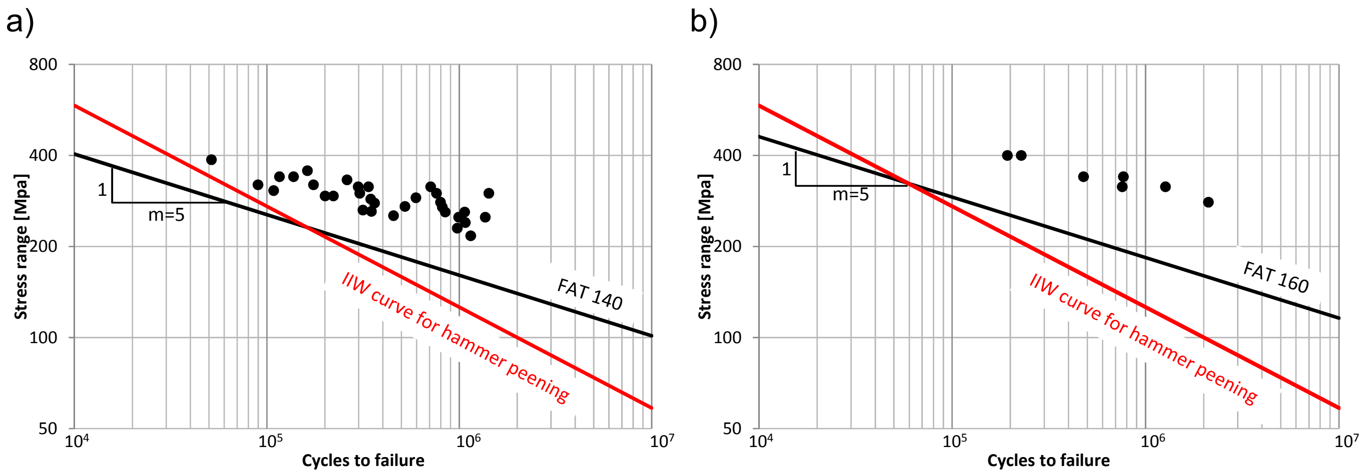


Figure 7. Available data for HFMI treated transverse welds shown in relation to the design curves proposed in Table 6: a) $355 < f_y \leq 550$ and b) $550 < f_y \leq 750$

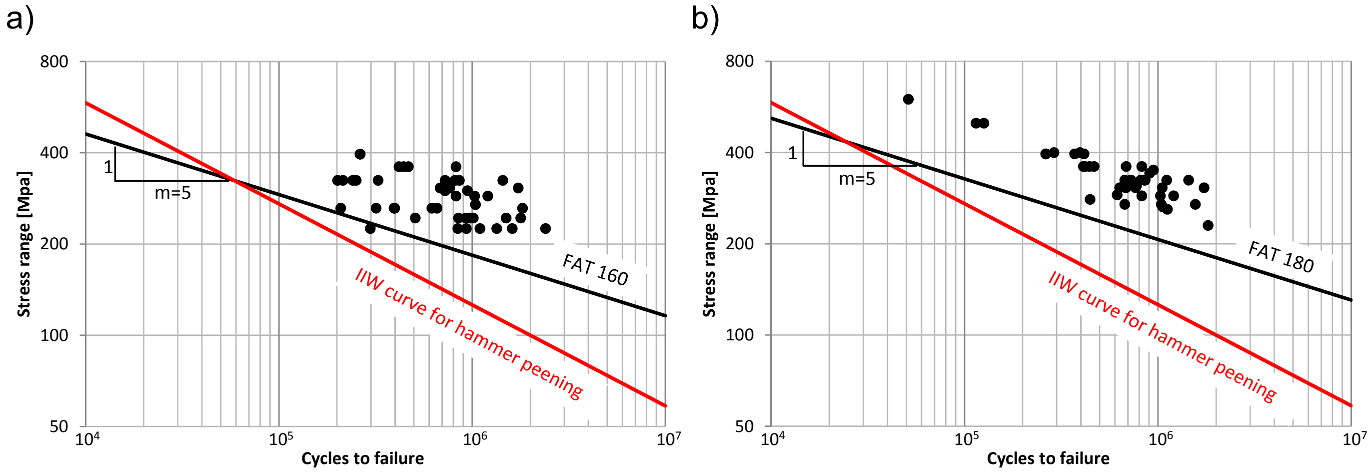


Figure 8. Available data for HFMI treated butt welds shown in relation to the design curves proposed in Table 6: a) $355 < f_y \leq 550$ and b) $550 < f_y \leq 750$