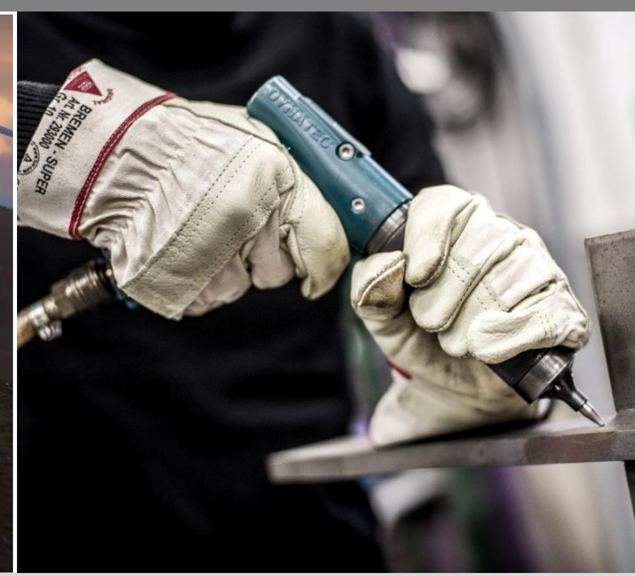
Increasing the fatigue strength of welded steel structures by high frequency mechanical impact treatment

Workshop 2: Study of structural and foundation systems of Wind Turbines

Dr.-Ing. Philipp Weidner, Prof. Dr.-Ing. Thomas Ummenhofer

Research Center for Steel, Timber & Masonry | Head: Prof. Dr.-Ing. T. Ummenhofer



Sub-structures of Offshore Wind Turbines (OWTs)

- **Jacket structures**

- sub-structures: Application of CHS (Circular Hollow Sections) with large wall thickness
- framework structure + transition piece + tower → welded structures
- fatigue has a major impact and fatigue design is of great importance

Research work at KIT focuses on methods that increase the fatigue strength of welded steel structures

Component design under fatigue loading: Efficient use of post weld treatment methods

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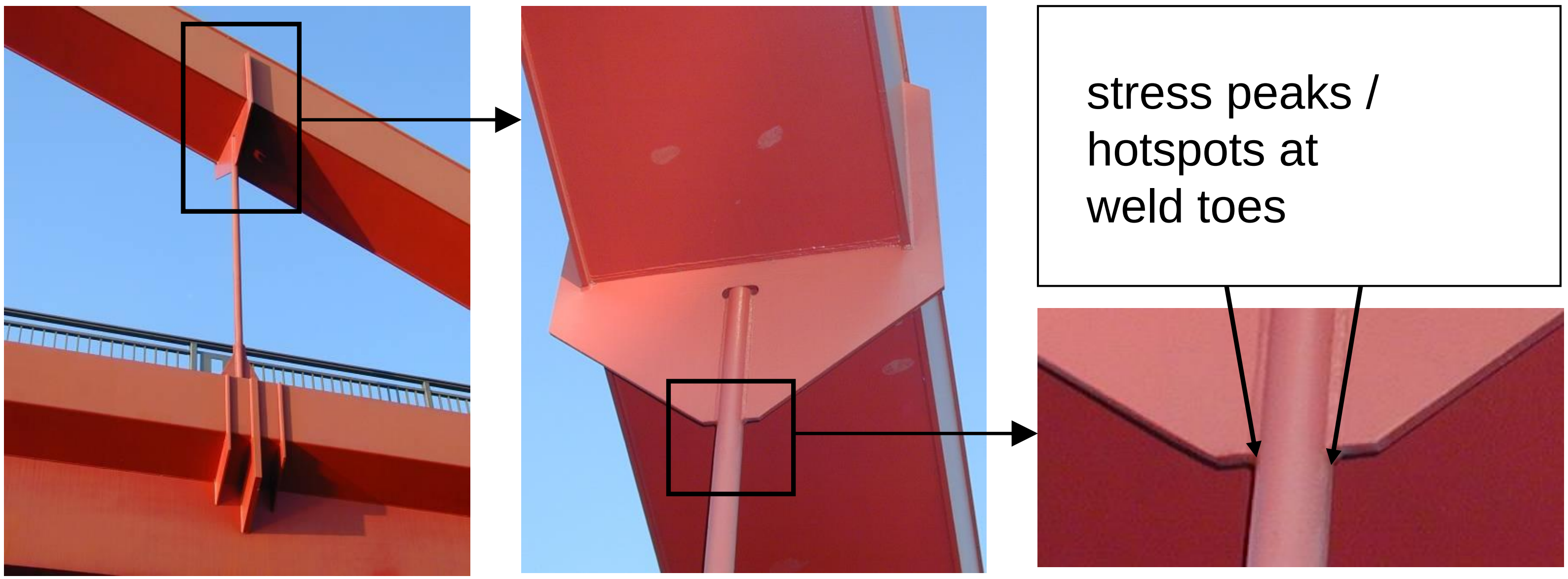
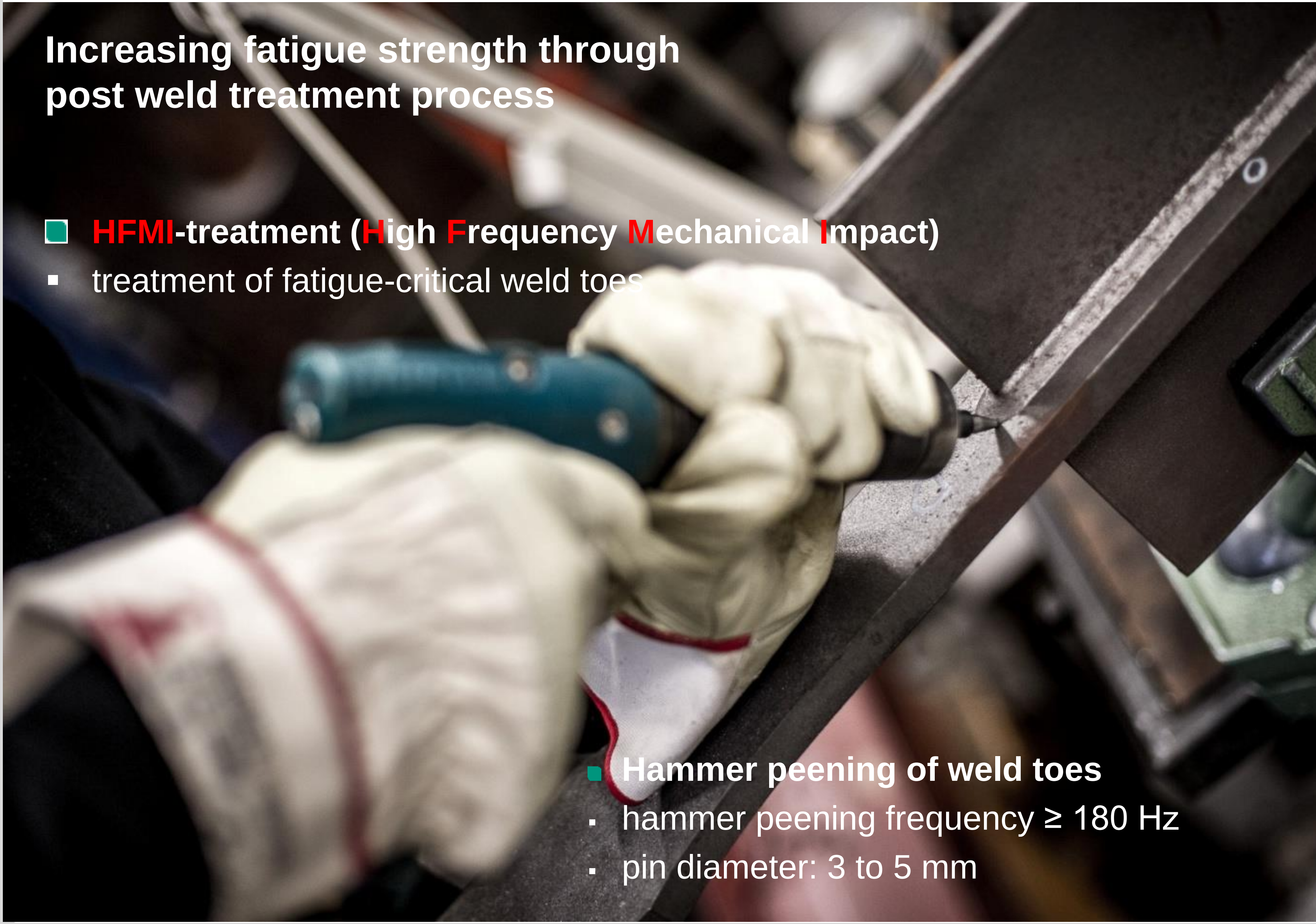
- Design- and material-related notches determine the service life
- Weld toes: notches with high stress concentrations



- Increase in local fatigue strength can extend life of entire structure

➡ **Application of post weld treatment methods**

Increasing fatigue strength through post weld treatment process



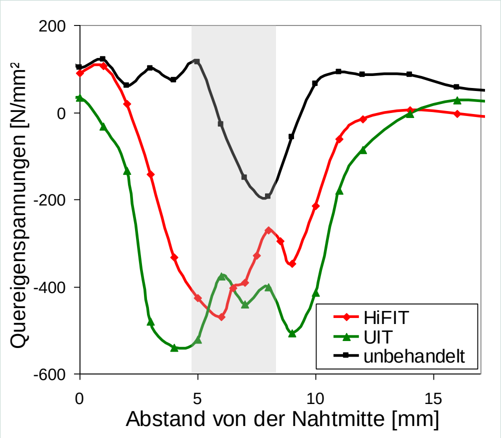
- **HFMI-treatment (High Frequency Mechanical Impact)**
  - treatment of fatigue-critical weld toes

- **Hammer peening of weld toes**
  - hammer peening frequency ≥ 180 Hz
  - pin diameter: 3 to 5 mm

HFMI-treatment: Effects

- HFMI: extremely effective technique in order to increase the fatigue strength of welded structures

High frequency mechanical impact treatment of weld toe

local increase of resistance against fatigue crack initiation	insertion of compressive residual stresses
	

- **Increase of fatigue strength by combination of both effects**

Findings of completed research projects : Enhancement of life time for mild and high strength steels

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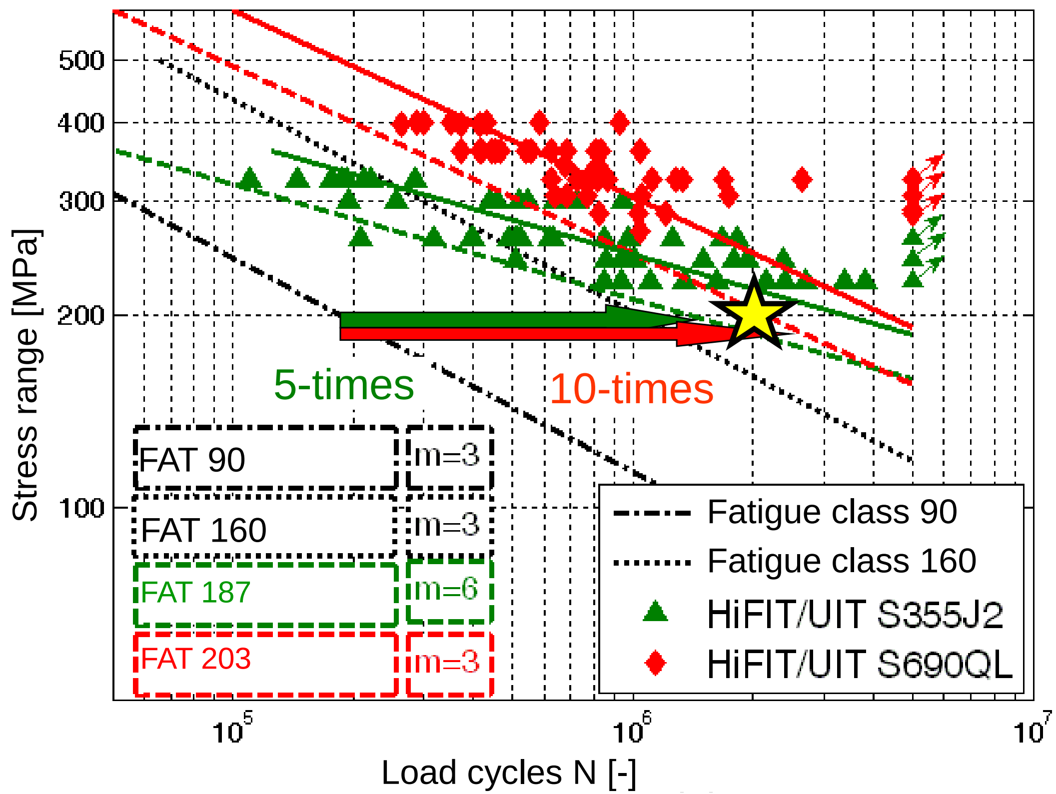
- **Effectiveness of HFMI can be determined on the basis of S-N curve position and its slope**
- fatigue strength $\Delta\sigma_c$ at $N_c = 2 \cdot 10^6$ cycles
- **Results of HFMI-treated butt-welds** (steel grades S355J2 and S690QL)
- increase of fatigue strength by 80 – 100% compared to design S-N curve
- slope of S-N curve more shallow
- benefit of treatment increases with increasing yield strength



Application of HFMI-treatment for new constructions

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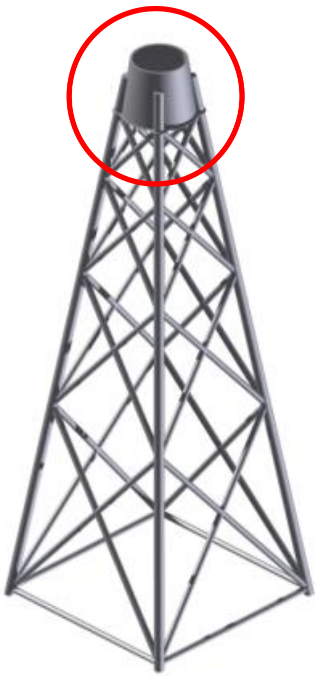
- **Transition piece of jacket-structure**
  - contains different types of constructional details / welded joints

transition piece



- **Circumferential welds of monopiles (made from both sides)**

Application of HFMI-treatment for new constructions: Treatment on fatigue critical welds

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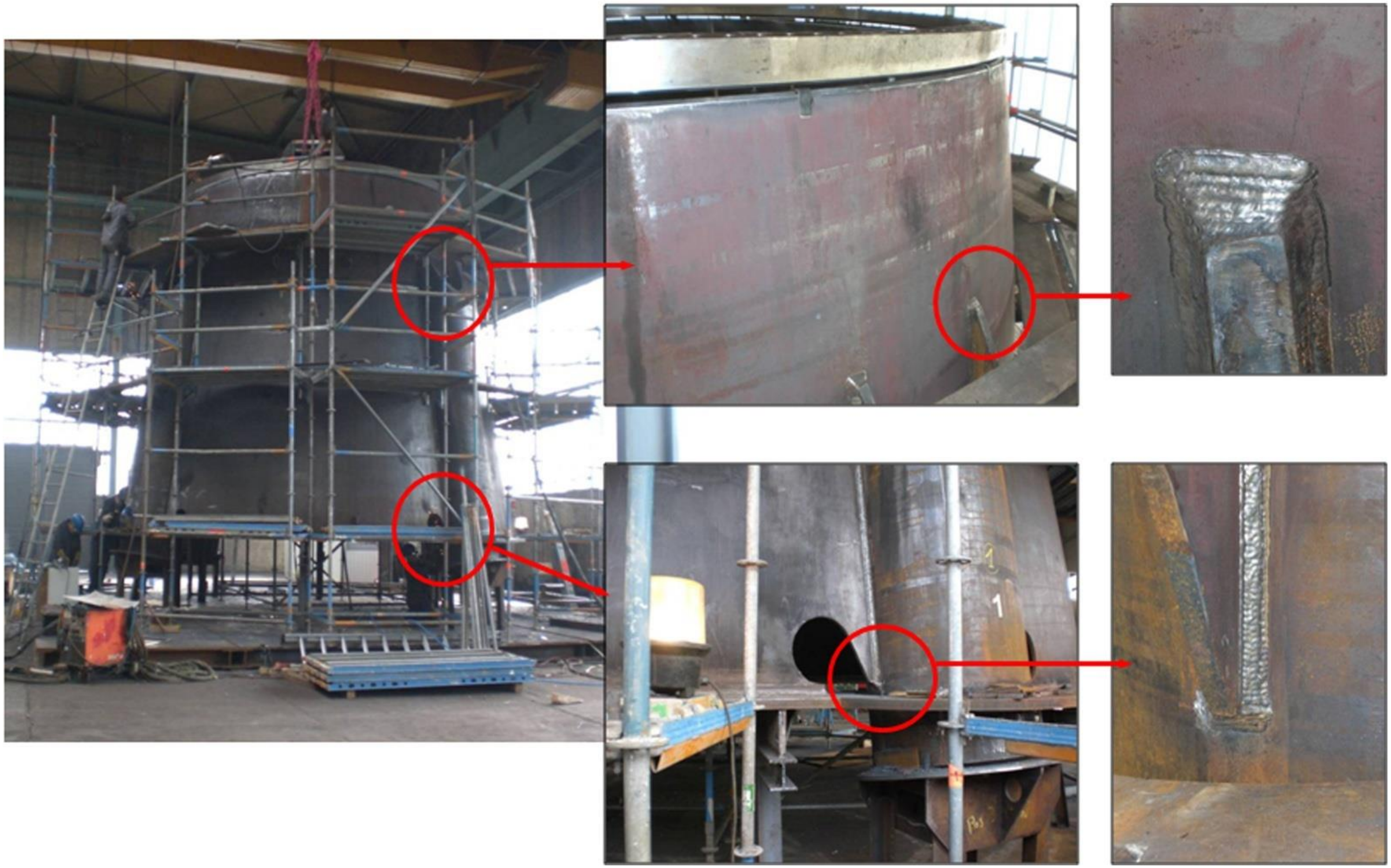
- **Transition piece of jacket structures: Hot spots to be treated by HFMI-methods**



Application of HFMI-treatment for new constructions

- **Bridge over Schenkendorfstraße in Munich**: HiFIT-treatment

Application of HFMI-treatment for existing structures

- **Rhine bridge in Karlsruhe:** HiFIT-treatment

Application of HFMI-treatment for existing structures

- **HiFIT-treatment of a structure subsequent to weld repair**

Initial situation

fatigue strength-increasing effect

effectiveness increases with increasing yield strength

improvement can not be included in fatigue design

so far application possible for new constructions via approval in individual cases (ZiE)

- **DASt-Guideline (German Committee for Steel Construction):** important contribution to the future practical application in construction (recognized technical rules and regulations)
- **Research project:** Development of a design concept as a basis for a DAST-Guideline

German Committee for Steel Construction - DASt:
Development of a DASt-Guideline for HFMI-treatment

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Universität Stuttgart

- **Research objectives**
  - **design concept** for HFMI-treated welds
  - determination of **fatigue-relevant influences**
  - definition of **application limits**

- **HFMI-methods**
  - HiFIT, Pitec, UIT

- **Experimental investigations**
  - fatigue tests on small scale specimens and components

Database
Own experiments and collection from literature

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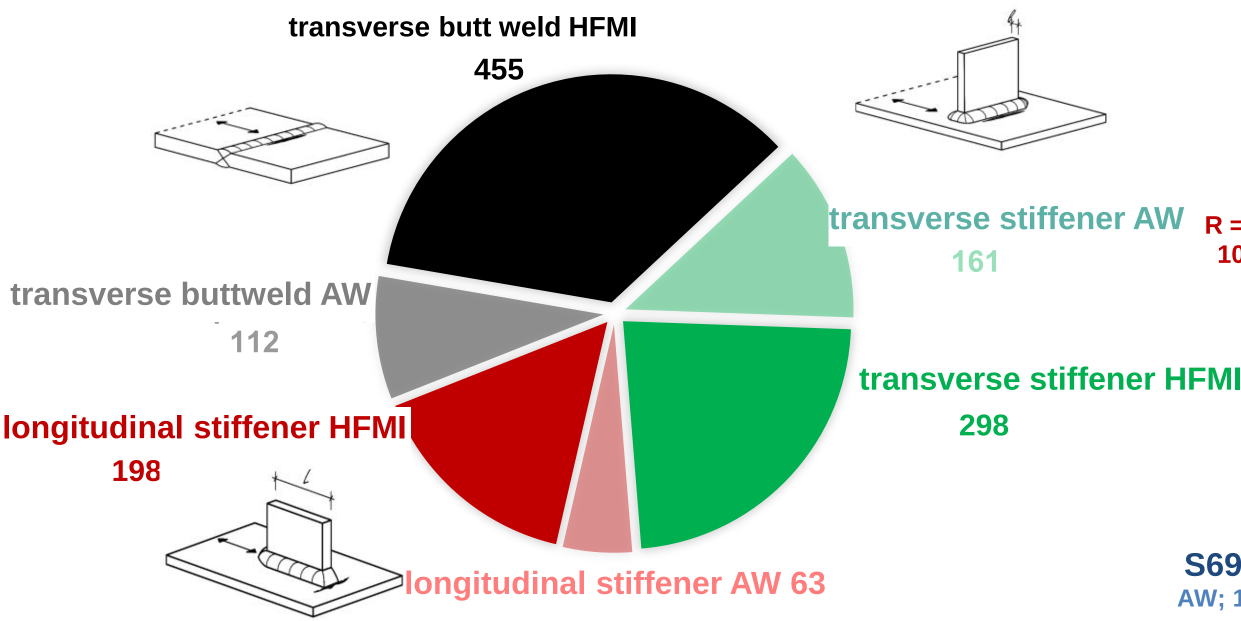
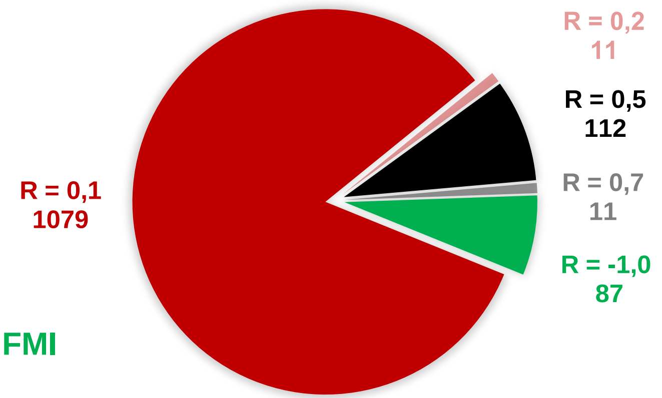
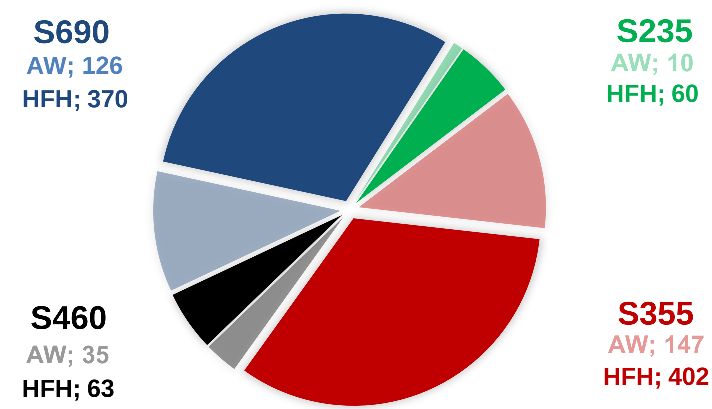
Scope of the database





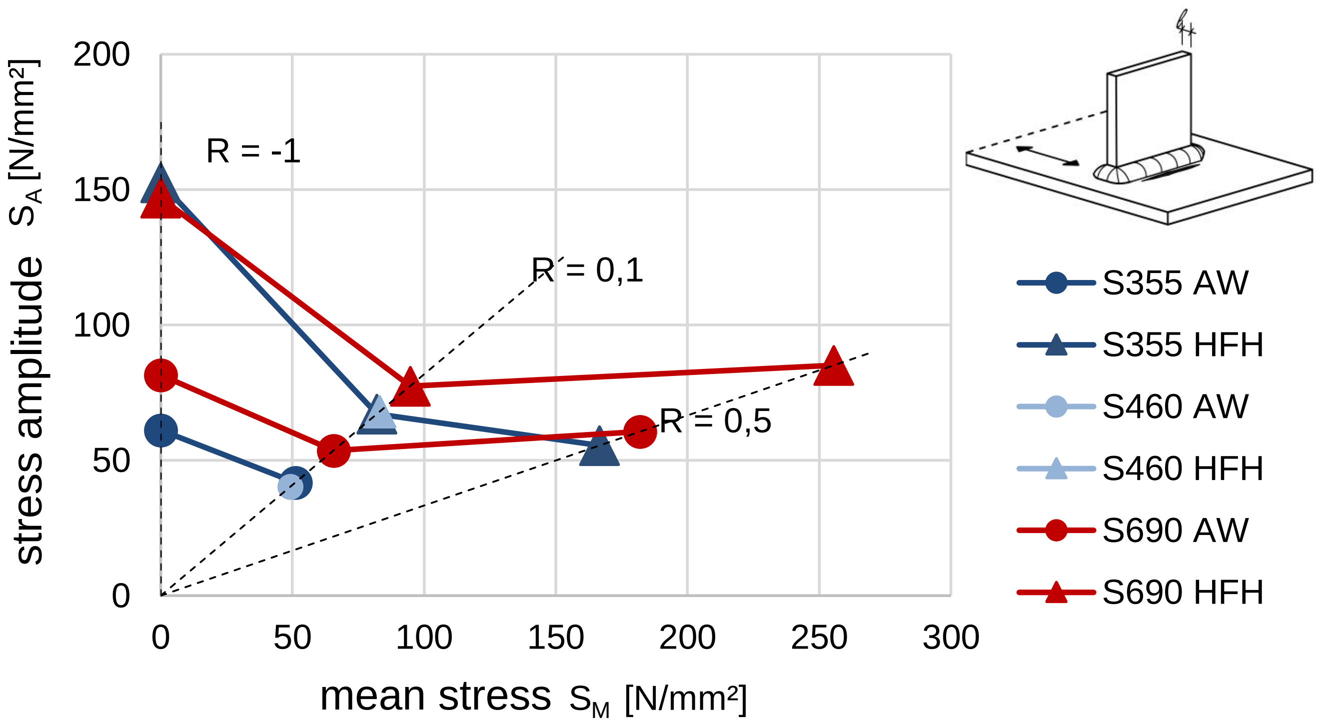


Quantification of fatigue-related influences with the aid of the database

- stress ratio R, yield strength influence, geometrical influences, effect of overloads
- definition of application limits

Quantification and evaluation of the influences

- **Influence of mean stress, using the example of the transverse stiffener**
  - Haigh diagram: plot of the stress amplitude S_A versus the mean stress S_M



- **Influence of mean stress for untreated (AW) and HFMI-treated test series clearly evident**
- **Beneficial effect at R = -1.0**

Design concept of DASt-Guideline 026

- **Concept requirements**
- based on **nominal stress concept according to DIN EN 1993-1-9**
- clear application limits
- safety of the design
- user-friendliness
- clarity
- Guideline for designing engineer:

→ in steel and composite bridge construction

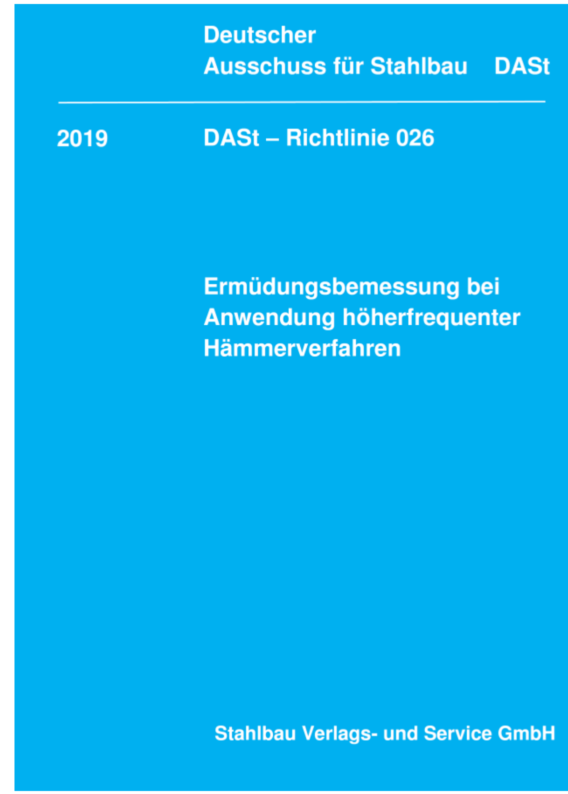
→ wind energy sector

→ crane runway constructions

DASt-Guideline 026

Fatigue design of welded joints subjected to High Frequency Mechanical Impact Treatment

1. Table of Contents
2. Scope of application
3. Constructional details
4. Limitations
5. Design concept
6. Design tables
7. Threshold for beneficial effect of HFMI-treatment
8. Design requirements for constructional details



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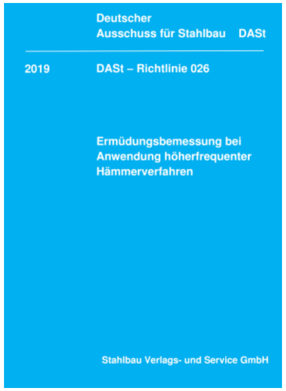

2. Scope of application

Steel grades

S235 to S700

Plate thickness

- $t \geq 5$ mm
- consideration of plate thickness, if influence confirmed

Stress ratio R

$-1{,}0 \leq R \leq 0{,}5$

Qualified HFMI-Methods

- **HiFIT** (High Frequency Impact Treatment)
- **PIT** (Pneumatic Impact Treatment)
- **UIT** (Ultrasonic Impact Treatment)

Application limits

- $\Delta\sigma \leq 1{,}5\, f_y$
- $-0{,}8\, f_y < \sigma \leq f_y$

max. achievable FAT-class

160
(≙ fatigue strength of basic material)

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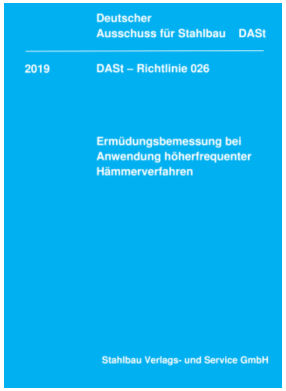
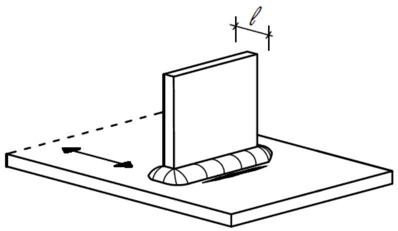
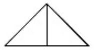
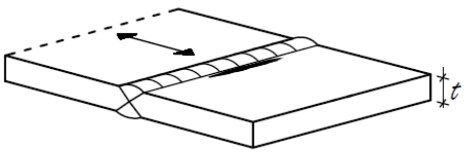
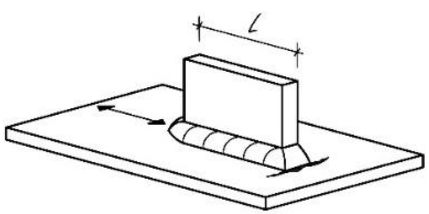
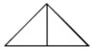


3. Constructional details

Design of the constructional detail	Weld symbol	Description
		Transverse stiffener EN 1993-1-9 Tab. 8.4, Detail 6
		Transverse butt weld EN 1993-1-9 Tab. 8.3, Detail 5
		Longitudinal stiffener EN 1993-1-9 Tab. 8.4 Detail 1

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4. Limitations

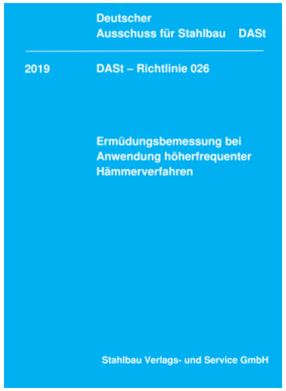
- Not regulated by the DASt guideline:

▪ HFMI treatment for weathering resistant structural steels

▪ constructional details galvanized after or before HFMI treatment

▪ Welding or component post-treatment after HFMI-treatment (TIG-dressing, grinding, stress relieving processes)

▪ HFMI-treated constructional details that have been loaded beyond the application limits



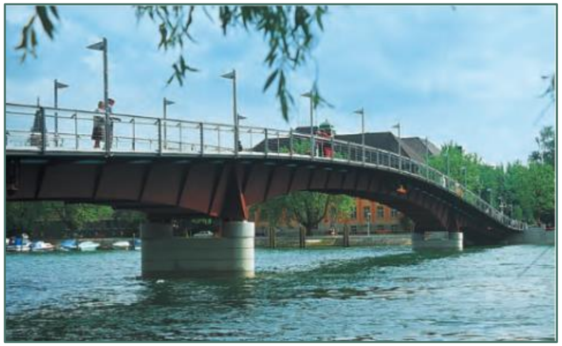


figure: Merkblatt 434 – Wetterfester Baustahl, Stahl-Informations-Zentrum

figure: Klaus Raiser GmbH & Co. KG

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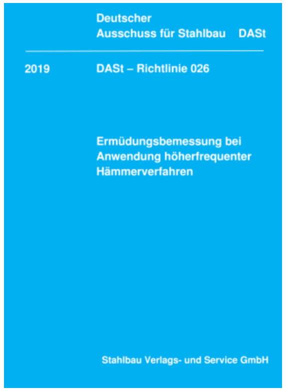


5. Design concept

- Based on nominal stress concept and constructional details according to DIN EN 1993-1-9

5 Fatigue verification

(1) The fatigue verification for as-welded constructional details according to the nominal stress method of EN 1993-1-9 is performed with Equation (3) where $\Delta\sigma_{C,aw}$ denotes the reference value of the fatigue strength for $N_C = 2x10^6$ cycles for as-welded state provided by EN 1993-1-9. For the verification of the HFMI-treated constructional details, $\Delta\sigma_{C,aw}$ may be replaced by $\Delta\sigma_{C,HFMI}$, see Equation (4).

(2) The fatigue verification of HFMI-treated constructional details is performed with Equation (4) where $\Delta\sigma_{C,HFMI}$ is provided by Tables 2, 4 and 6 for the considered constructional details.

$$\gamma_{Ff} \ \Delta\sigma_{E,2} \leq \Delta\sigma_{C,aw} / \gamma_{Mf} \qquad (3)$$

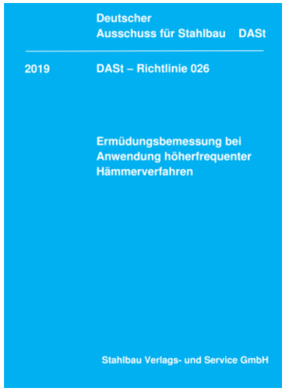
$$\gamma_{Ff} \ \Delta\sigma_{E,2} \leq \Delta\sigma_{C,HFMI} / \gamma_{Mf} \qquad (4)$$

with $\Delta\sigma_{E,2}$, γ_{Ff} and γ_{Mf} according to EN 1993-1-9;

and $\Delta\sigma_{C,HFMI}$ according to Table 2, 4 and 6 of this DASt-guideline.

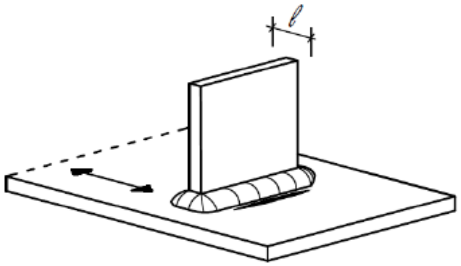
after HFMI treatment: stepwise increase of fatigue strength depending on material yield strength

DASt-Guideline 026



6. Design tables

- **Transverse stiffener:** Improved fatigue strength $\mathbf{\Delta\sigma_{c,HFMI}}$

	**Improved fatigue strength $\Delta\sigma_{C,HFMI}$ [N/mm²]** 1), 3), 4)		
	Stress ratio R [-] 2)		
Steel grade S acc. to EN 10025	**-1,0**	**0,1**	**0,5**
S235 ≤ S < S355	100	100	80
S355 ≤ S < S550	160	140	90
S550 ≤ S ≤ S700	160	160	125

1) Table is valid for $\ell \le 50$ mm; if $50 < \ell \le 80$ mm, $\Delta\sigma_{C,HFMI}$ should be reduced by one fatigue detail category.

2) For other stress ratios R, linear interpolation is allowed.

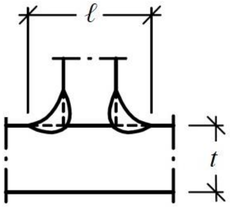
3) Stress range limitation: $\Delta\sigma \le 1{,}5\, f_y$

4) Stress peak limitation: $-0{,}8\, f_y < \sigma \le f_y$

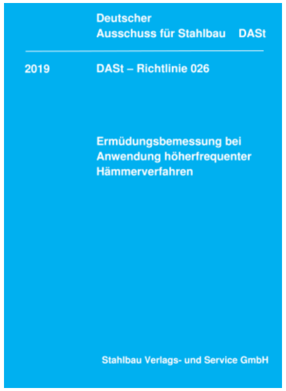
basic FAT class 80
→ Improvement
up to 100%

5-fold lifetime
at $\Delta\sigma$ = 140N/mm²

36-fold lifetime
at $\Delta\sigma$ = 90N/mm²

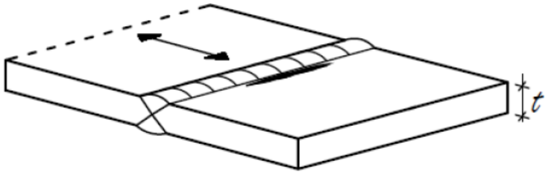


DASt-Guideline 026



6. Design tables

- **Transverse butt weld:** Improved fatigue strength $\boldsymbol{\Delta\sigma_{c,HFMI}}$



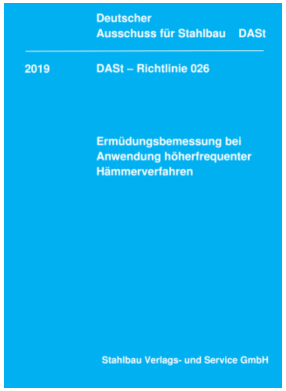
Steel grade S acc. to EN 10025	Improved fatigue strength $\Delta\sigma_{C,HFMI}$ [N/mm²] 3), 4), 5) Stress ratio R [-] 2) -1,0	0,1	0,5
S235 ≤ S < S355	1.)	1.)	1.)
S355 ≤ S < S550	160	140	100
S550 ≤ S ≤ S700	160	$\boxed{160}$	140

1) No improved fatigue detail category due to missing data base.
2) For other stress ratios R, linear interpolation is allowed.
3) Stress range limitation: $\Delta\sigma \leq 1{,}5\ f_y$
4) Stress peak limitation: $-0{,}8\ f_y < \sigma \leq f_y$
5) For t > 25 mm, $\Delta\sigma_{C,HFMI}$ should be reduced by $k_s = (25/t)^{0,2}$

basic FAT class 90
→ Improvement
up to 77%

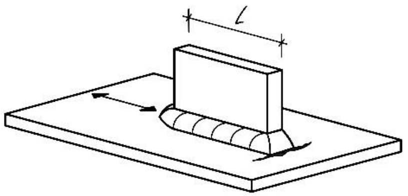
5-fold lifetime
at $\Delta\sigma$ = 160 N/mm²

DASt-Guideline 026



6. Design tables

- **Longitudinal stiffener:** Improved fatigue strength $\Delta\sigma_{c,HFMI}$

	**Improved fatigue strength $\Delta\sigma_{C,HFMI}$** [N/mm²] 1), 4), 5), 6)		
	Stress ratio R [-] 3)		
Steel grade S acc. to EN 10025	**-1,0**	**0,1**	**0,5**
S235 ≤ S < S355	2.)	2.)	2.)
S355 ≤ S < S550	112	$\boxed{112}$	80
S550 ≤ S ≤ S700	125	125	80

1) Table is valid for stiffener lengths with ℓ > 100 mm corresponding with as-welded detail category 56 in EN 1993-1-9:2005. Due to missing database, the beneficial effect and the improved fatigue strength $\Delta\sigma_{C,HFMI}$ of shorter stiffener lengths ℓ ≤ 100 mm could not be quantified. Nevertheless, the application of Table 7 for shorter stiffener lengths ℓ ≤ 100 mm is considered safe-sided.

2) No improved fatigue detail category due to missing data base.

3) For other stress ratios R, linear interpolation is allowed.

4) Stress range limitation: $\Delta\sigma \leq 1{,}5\ f_y$

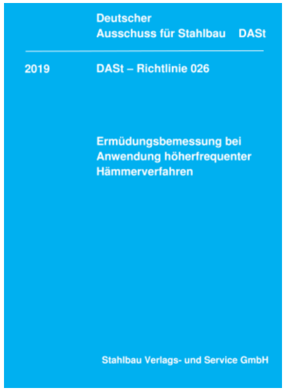
5) Stress peak limitation: $-0{,}8\ f_y < \sigma \leq f_y$

6) For longitudinal stiffener in pure bending, the fatigue strength $\Delta\sigma_{C,HFMI}$ should be reduced by one fatigue detail category.

basic FAT class 56
→ Improvement
up to 123%

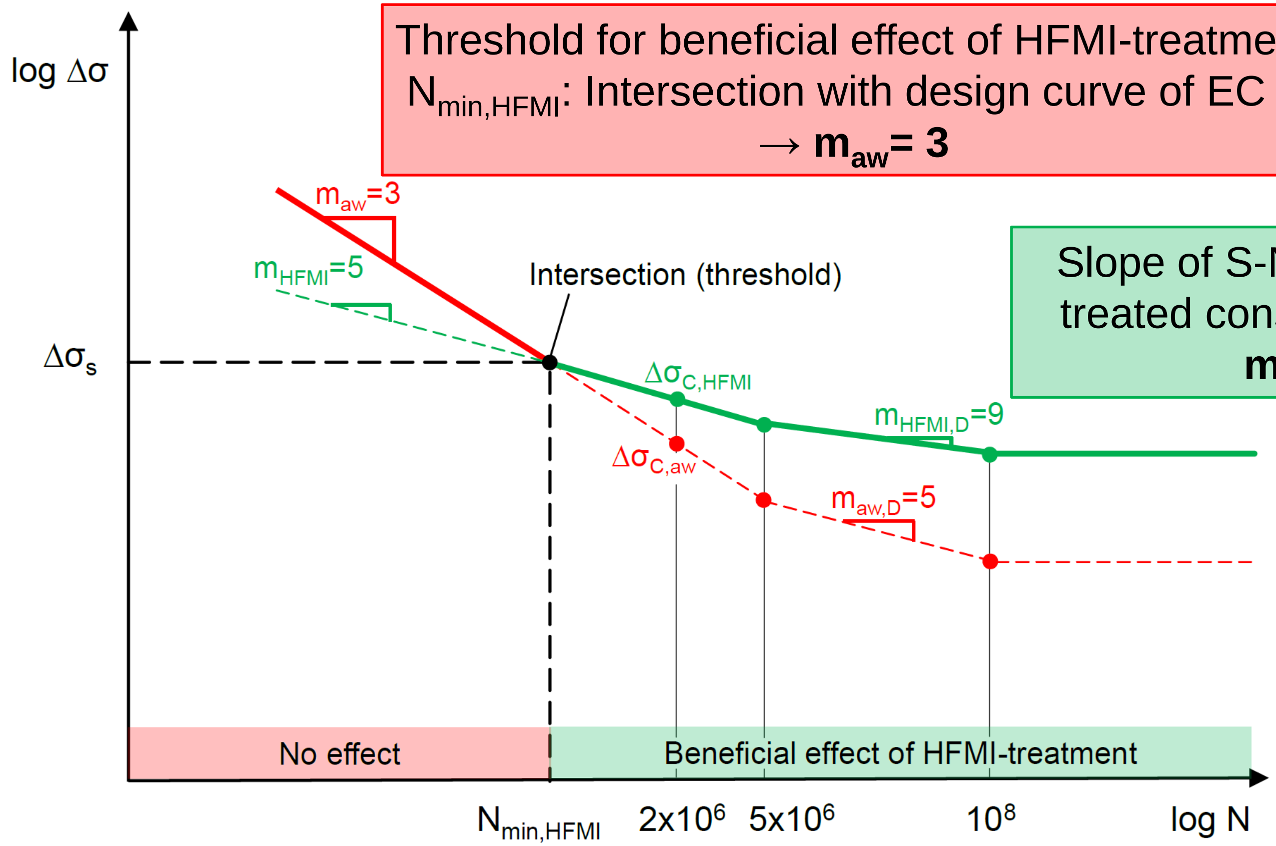
8-fold lifetime
at Δσ = 112 N/mm²

DASt-Guideline 026



7. Threshold for beneficial effect of HFMI-treatment

Threshold for beneficial effect of HFMI-treatment
$N_{min,HFMI}$: Intersection with design curve of EC 3
$\rightarrow$ **m_{aw}= 3**



Slope of S-N curve for HFMI-treated constructional details
m_{HFMI} = 5

For numbers of cycles ($5 \cdot 10^6 < N < 10^8$):
$m_{HFMI,D}$ = 9

Number of cycles ≥ $N_{min,HFMI}$: HFMI-treatment computationally applicable and beneficial
($\rightarrow$ $N_{min,HFMI}$ and associated stress range $\Delta\sigma_s$ in tabular form)

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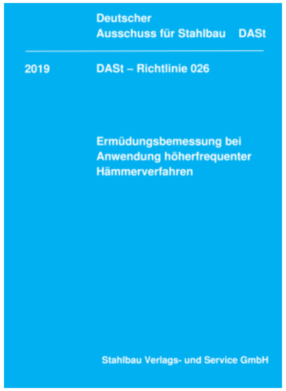
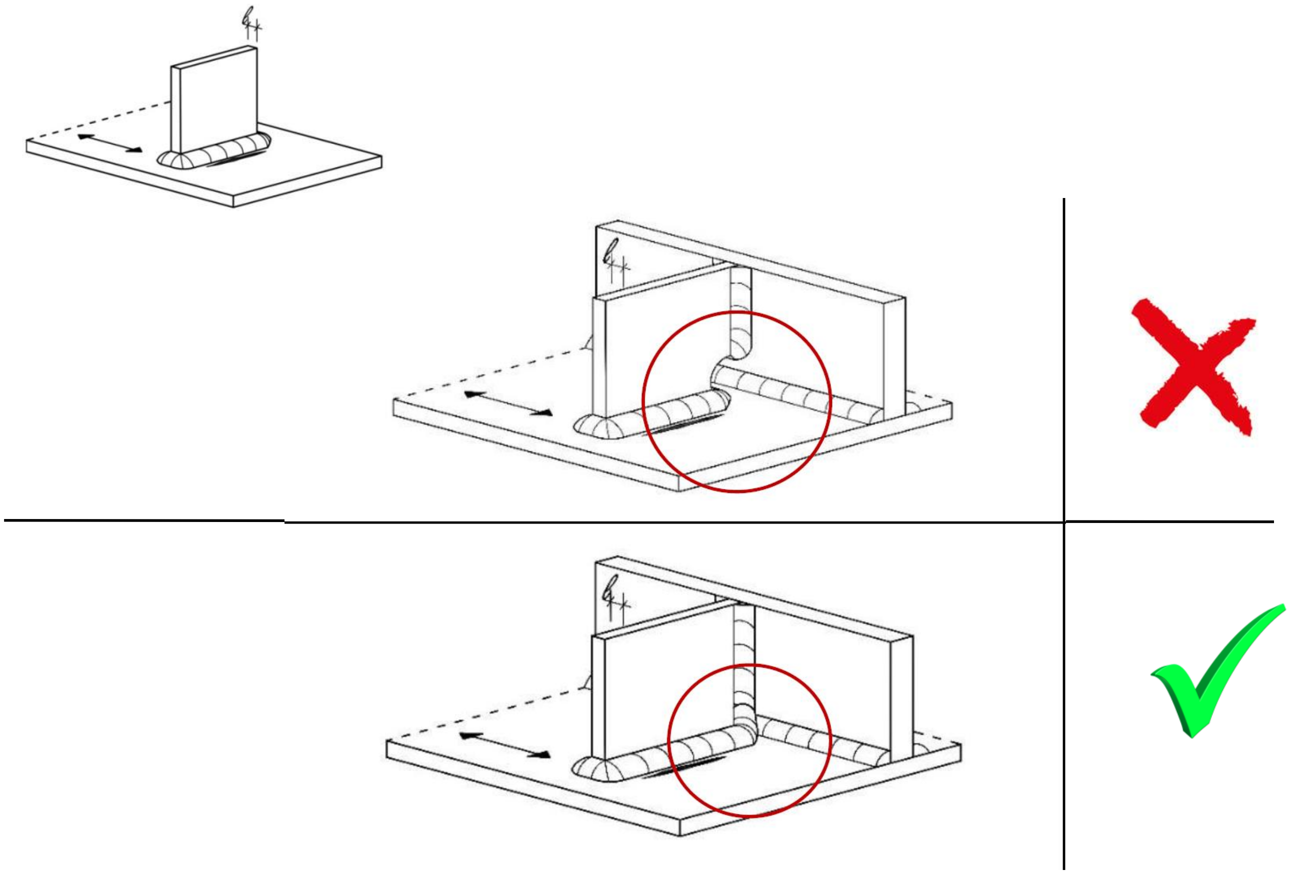
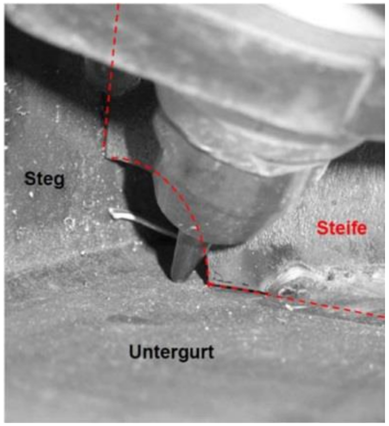


8. Design requirements for constructional details

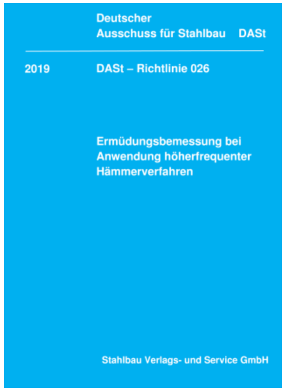
- HFMI application requires accessibility



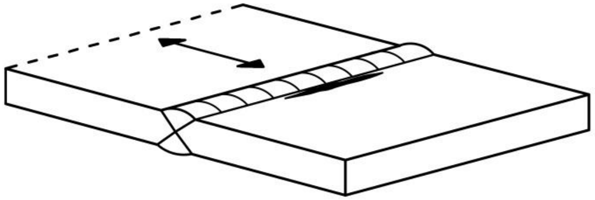
practical test on
circular free cut
r = 30 mm



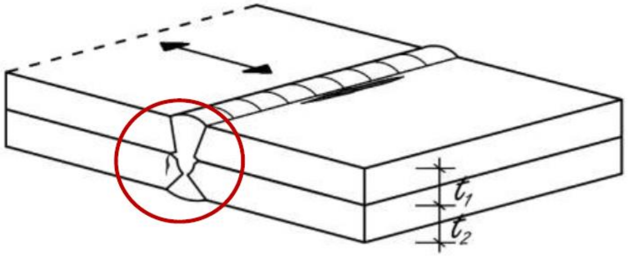
DASt-Guideline 026



8. Design requirements for constructional details



- **Transverse lamella joint** due to risk of crack on the root of the end groove weld



Summary

- **DASt Guideline 026** was developed on the basis of experimental and numerical investigations

Deutscher
Ausschuss für Stahlbau DASt

2019 DASt – Richtlinie 026

Ermüdungsbemessung bei Anwendung höherfrequenter Hämmerverfahren

Stahlbau Verlags- und Service GmbH

- **DASt Guideline 026**: Basis for extension of EC 3 Part 1-9 (next generation of standards → Annex F)

➔ **HFMI treatment will be covered**

CEN/TC 250

Date: 2019-10

prEN 1993-1-9:2020

Secretariat: BSI

Eurocode 3:— Design of steel structures— Part 1.9: Fatigue

Eurocode 3:— Bemessung und Konstruktion von Stahlbauten — Teil: 1.9 Ermüdung

Eurocode 3:— Calcul des structures en acier central — Partie 1.9: Fatigue

ICS:

Second draft*-v.04 2019-10-31*

CCMC will prepare and attach the official title page.

Increasing the fatigue strength of welded steel structures by high frequency mechanical impact treatment

Workshop 2: Study of structural and foundation systems of Wind Turbines

Dr.-Ing. Philipp Weidner, Prof. Dr.-Ing. Thomas Ummenhofer

Research Center for Steel, Timber & Masonry | Head: Prof. Dr.-Ing. T. Ummenhofer

Literature

[1] DASt-Richtlinie 026 (2019) *Ermüdungsbemessung bei Anwendung höherfrequenter Hämmerverfahren*, Deutscher Ausschuss für Stahlbau DASt.

[2] Kuhlmann, U.; Breunig, S.; Ummenhofer, T.; Weidner, P. (2017) Entwicklung einer DASt-Richtlinie für Höherfrequente Hämmerverfahren, IGF Nr. 17886, DASt-AiF Schlussbericht.

[3] Kuhlmann, U.; Breunig, S.; Gölz, L. (2019) Untersuchungen zur Auswirkung variierender Ausführungsqualitäten einer HFH-Nachbehandlung und Beurteilung einfacher Methoden zur Überprüfung der Nachbehandlungsspur, Schlussbericht, Bundesanstalt für Wasserbau (BAW).

[4] Ummenhofer, T.; Weidner, P.; Kuhlmann, U.; Kudla, K.; Breunig, S. (2017) Entwicklung eines einfachen Qualitätssicherungstests für die Anwendung höherfrequenter Hämmerverfahren, FOSTA-Schlussbericht P872.

[5] DIN 50159-1:2015-01 (2015) Metallische Werkstoffe – Härteprüfung nach dem UCI-Verfahren – Teil 1: Prüfverfahren, Beuth, Berlin.

[6] Breunig, S. (2021) Bewertung der Ermüdungsfestigkeit von Schweißnähten und ihrer Nachbehandlung im Brückenbau, Dissertation, Universität Stuttgart.

[7] Ummenhofer, T., Herion, S., Hrabowski, J., Rack, S., Weich, I., Telljohann, G., Dannemeyer, S., Strohbach, H., Eslami-Chalander, H., Kern, A., Pinkernell, S., Smida, M., Rahlf, U., Senk, B.: Lebensdauerverlängerung neuer und bestehender geschweißter Stahlkonstruktionen. REFRESH-Projekt, Schlussbericht Projekt P702, Forschungsvereinigung Stahlanwendung e.V. FOSTA, 2009.