Fatigue of very large high-strength bolting assemblies in wind turbines

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Outline

- High-strength bolts in wind turbines
- Experimental fatigue assessment
  - Test results on HV-bolt sets M36 and M64
  - Validation of normative S-N curves
- Analytical fatigue assessment
- Conclusions
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Bolted ring-flange connections in wind turbines

- Up to 200 high-strength bolt assemblies (System HV) per connection
- High loads with large number of load cycles
Preloading and hot-dip galvanizing

Preloading for limitation of fatigue loads

- Nominal preload $F_{p,C}^* = 0.7 \cdot R_{p0.2} \cdot A_{sp}$
- High mean stress affects the fatigue strength of bolts

Hot-dip galvanizing for corrosion protection

- Lower fatigue strength as uncoated structural components
- Fatigue cracks initiated at shrinkage cracks in the zinc layer

Limited validation of fatigue characteristics and normative S-N curves for large bolt diameters

Source: Simonsen (2015)
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Fatigue tests on large-size HV-bolt sets

- M36 and M64 HV-bolt sets (10.9), rolled before head treatment
- Fatigue tests with constant stress amplitudes and high mean stress
  \[ S_m = 0.7 \cdot R_{p0.2} = 630 \text{ N/mm}^2 \]
- Test series for 3 boundary layer conditions:
  - Black bolts (B)
  - Normal temperature hot-dip galvanized (NT)
  - High temperature hot-dip galvanized (HT) only M36

  Influence of hot-dip galvanizing

  Assessment of the “size effect”
Fatigue tests on large-size HV-bolt sets

**M36 - tests**

*High frequency pulsator*

- Mean load 515 kN
- Testing frequency ca. 50 Hz
- Over 100 specimens

![M36 test setup](image)

**M64 - tests**

*Servo-hydraulic testing machine*

- Mean load 1680 kN
- Testing frequency 2-4 Hz
- 18 specimens

![M64 test setup](image)
Fatigue tests on HV-bolt sets M36

Mean stress $S_m = 0.7 \cdot R_{p0.2} = 630$ N/mm$^2$

- 50% Survival probability
- Rupture
- Run-out

Decrease of fatigue strength in accordance with guideline VDI 2230

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Fatigue tests on HV-bolt sets M64

Results in comparison to M36 bolts

**Black bolts**

Mean stress $S_m = 0.7 \cdot R_{p0.2} = 630 \text{ N/mm}^2$

Survival probabilities:
- $\ldots$ $Ps = 50 \%$
- $\ldots$ $Ps = 10 \%$
- $\ldots$ $Ps = 90 \%$

Transition region to endurance limit

Load cycles $N [-]$

Nominal stress amplitude $S_a [\text{N/mm}^2]$

Transition region to endurance limit

Run-outs

$5 \cdot 10^5$

HCF - Range

Fatigue tests on HV-bolt sets M64
Fatigue tests on HV-bolt sets M64

Results in comparison to M36 bolts

NT-galvanized bolts

Mean stress $S_m = 0.7 \cdot R_{p0.2} = 630 \text{ N/mm}^2$

Survival probabilities:
- $Ps = 50 \%$
- $Ps = 10 \%$
- $Ps = 90 \%$

Load cycles $N \ [\text{-}]$

Nominal stress amplitude $S_a \ [\text{N/mm}^2]$

Transition region to endurance limit

Run-outs

HCF - Range

$5 \cdot 10^5$
Fatigue tests on large-size HV-bolt sets

Comparison to S-N curves from Eurocode 3

Hot-dip galvanized bolts

Nominal stress amplitude $S_a \text{[N/mm}^2\text{]}$

Load cycles $N \text{[-]}$

Rupture M36
Rupture M64
Rupture M48 (Marten)

Run-outs

Size reduction:

$\Delta S_{c,\text{red}} = \left( \frac{30}{\varnothing} \right)^{0,25} \cdot \Delta S_c$

M36: $0,96 \cdot \Delta S_c$
M48: $0,89 \cdot \Delta S_c$
M64: $0,83 \cdot \Delta S_c$

Hot-dip galvanized bolts

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Evaluation of FAT-class and size-reduction acc. to Eurocode 3

M36 HV-bolts (tZn NT)

Nominal stress range $\Delta S$ [N/mm²]

- Rupture
- Run-out
- $P_s$,50%
- $P_s$,95%

Regression w/ fixed slope $m = 3$

$\Delta S (N = 2 \cdot 10^6) = 51.9$ N/mm²

$\Delta S_c$ (FAT 50, M36) = 47.8 N/mm²

EC3 – FAT 50 (w/o reduction)

Size reduction of EC3 FAT 50

Char. fatigue strength $\Delta S_c$ (N = 2 $\cdot 10^6$) [N/mm²]

Bolt diameter [mm]

Test result

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Evaluation of FAT-class and size-reduction acc. to Eurocode 3

Nominal stress range $\Delta S$ [N/mm²] vs. Load cycles $N$ [-]

- $\Delta S (N = 2 \cdot 10^6) = 48.4$ N/mm²
- $\Delta S_c (\text{FAT } 50, \text{M36}) = 44.5$ N/mm²

Regression w/ fixed slope $m = 3$

Size reduction of EC3 FAT 50

- w/o upper HCF test level
- $\Delta S_c (\text{FAT } 50, \text{M36}) = 44.5$ N/mm²

Rupture
- Run-out
- $P_s,50\%$
- $P_s,95\%$

M48 HV-bolts (tZn NT)

Bolt diameter [mm]

EC 3 FAT 50
- Test result

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**Fatigue tests on large-size HV-bolt sets**

**Evaluation of FAT-class and size-reduction acc. to Eurocode 3**

- **M64 HV-bolts (tZn NT)**
- **EC3 – FAT 50 (w/o reduction)**
- Regression w/ fixed slope \( m = 3 \)
- \( \Delta S (N = 2 \cdot 10^6) = 48,0 \text{ N/mm}^2 \)
- \( \Delta S_c (\text{FAT 50, M36}) = 41,4 \text{ N/mm}^2 \)
- \( \text{Char. fatigue strength } \Delta S_c (N = 2 \cdot 10^6) \text{ [N/mm}^2] \)
- \( \text{Load cycles } N \text{ [-]} \)
- \( \text{Char. fatigue strength } \Delta S_c \text{ [N/mm}^2] \)
- \( \text{Bolt diameter } \text{[mm]} \)

**Test result**

- **EC 3 FAT 50**
- **w/o upper HCF test level**
Fatigue tests on large-size HV-bolt sets

Comparison to S-N curves from Eurocode 3

Black bolts

Size reduction:

\[ \Delta S_{c,\text{red}} = \left( \frac{30}{\varnothing} \right)^{0.25} \cdot \Delta S_c \]

\( M36: 0.96 \cdot \Delta S_c \)
\( M64: 0.83 \cdot \Delta S_c \)
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Fatigue calculation with local concept (strain-life)

**FE-Model**

**Nominal loading**

Local stress $\sigma$ \[ N/mm^2 \]

Local strain $\varepsilon$ \[ - \]

Local hysteresis

**Damage parameter S-N curve ($P_{SWT}$)**

$$P_{SWT} = \sqrt{(\sigma_a + \sigma_m) \cdot \varepsilon \cdot E}$$

Load cycle number until initial crack $N_i$ [-]

**Non-linear material implementation**

**Preloading:**
monotonic material law

**Cyclic loading:**
cyclic stabilized material law

**Base material fatigue**
strain-life curve

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Fatigue calculation with local concept

Initial crack

Initial crack with cyclic relaxation

Crack propagation until rupture (additional)

\[ S_m = 0.7 \cdot R_{p0.2} \]

Test M36 (Ps, 50%)

Analytical:

- Initial crack (w/o relax.)
- Initial crack (with relax.)
- Rupture (with relax.)

Nominal stress amplitude \( S_a \) [N/mm²]
Load cycles \( N \) [-]

Load cycles \( N \) [-]

Local stress \( \sigma \)
Local strain \( \varepsilon \)

\[ \Delta \sigma_{o,Relax} \]
\[ \Delta \varepsilon_a \]
Fatigue calculation with local concept

\[ S_m = 0.7 \cdot R_{p0.2} \]

Test M36 (Ps,50%)

Initial crack (w/o relax.)

Initial crack (with relax.)

Rupture (with relax.)

Load cycles N [-]

Nominal stress amplitude \( S_a \) [N/mm²]

Effect of hot-dip galvanizing is not covered in analytical approach!
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Conclusions

- Fatigue capacity of high-strength, large-size bolts significantly affected by hot-dip galvanizing
- EC 3 fatigue class FAT50 confirmed for bolts up to diameter M64
- Size reduction necessary, better fatigue classification of uncoated bolts must be seen critically
- Analytical calculations with local concept show good approximation to experimental results for bolts w/o boundary layer influence
Thank you!

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