

Use of Hilti X-BT fasteners in steel towers for wind turbines

Fatigue classification of structural steel

Robustness of anchorage

Verification of fastenings to cast iron

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Summary

Hilti powder-actuated X-BT threaded fasteners allow efficient and fast attachments of components like cable ladders within the steel towers of wind turbines. Such towers are subjected to dynamic loading which requires fatigue verification of the structure. Therefore, the effect of X-BT fasteners on the fatigue strength of the structural steel has to be understood and classified within the relevant fatigue design standards.

This paper provides a survey on scope and results of a comprehensive experimental fatigue test program. Based on this investigation fatigue detail categories for the constructional detail "*Structural steel base material with the Hilti powder-actuated fastener X-BT*" were approved by GL (Germanischer Lloyd) and DNV (Det Norske Veritas). The effect of X-BT fasteners is less pronounced than the effect of welded studs. The presence of X-BT fasteners generally does not control the fatigue design of the welded tower. GL approved the detail category 90 according to Eurocode 3, EN 1993-1-9 and DNV approved the detail category C2 according to the standard DNV-RP-C203. Both allow higher fatigue utilization of the steel when comparing with welded stud connection.

Additionally the behaviour of X-BT fasteners subjected to varying loading will be briefly discussed in order to address all dynamic aspects. The pullout behaviour of the fasteners is not detrimentally affected by dynamic loading and they behave very robust with respect to the effect of vibration of the base material.

A new application field for Hilti X-BT threaded studs is their use for fastenings to cast iron components. Such components are often used in the nacelles of wind turbines. Based on comprehensive experimental investigations a reliable performance of X-BT fastenings made to cast iron – including also dynamic loading – was successfully verified.

1 Introduction into Hilti X-BT direct fastening technology

Since 2003 Hilti X-BT threaded fasteners are successfully used for fastening applications on coated steel structures in corrosive environments all around the globe.

Hilti X-BT threaded studs are powder-driven fasteners with a blunt tip, which are driven into a pre-drilled hole with a diameter of 4 mm. The shank diameter of the studs amounts to 4.5 mm. The anchorage of the fastener in the base metal is predominantly caused by friction welding. With respects to more details on the X-BT fastening technology it is referred to the Hilti product literature [1, 2]. A comprehensive introduction into direct fastening technology including the application of blunt tip fasteners is given in the *Stahlbau-Kalender 2005* [3]. Figure 1 shows the available fasteners and gives information on relevant applications for the respective types.




		
X-BT M10-24-6 SN12-R X-BT W10-24-6 SN12-R	X-BT M8-24-6 SN12-R	X-BT M6-24-6 SN12-R X-BT W6-24-6 SN12-R
Typical application: Fastening of cables, cable ladders, T-bars, grounding	Typical application: Fastening of grating and Hilti M-channels	Typical application: Fastening of electrical junction boxes
Recommended working loads [1, 2]: Base material S235 (A36) : Tension: $N_{rec} = 1.8 \text{ kN}$ (405 lbs), Shear: $V_{rec} = 2.6 \text{ kN}$ (517 lbs) Base material S355 (Grade 50) : Tension: $N_{rec} = 2.3 \text{ kN}$ (584 lbs), Shear: $V_{rec} = 3.4 \text{ kN}$ (764 lbs)		

Figure 1. Survey of Hilti X-BT threaded fasteners

Figure 2 shows a sketch of an installed X-BT fastener. Its key benefit is that it can be driven into coated base metal with a thickness $t \geq 8 \text{ mm}$ without damage of the back side coating, as no penetration of the steel plate occurs. On the entrance side the base steel is covered by a sealing washer preventing access of moisture. Neither preparation nor rework of the steel coating is required at the fastening locations.

The fasteners are made from proprietary austenitic or ferritic-austenitic stainless material allowing the use in C5 environments, e.g. for fastening metal or fiber grating on off-shore platforms or next to the foundation of off-store steel towers. The durability of the X-BT threaded fasteners is also investigated and verified by means of corrosion tests of samples which are exposed for many years to the sea and sea-water environment [4].

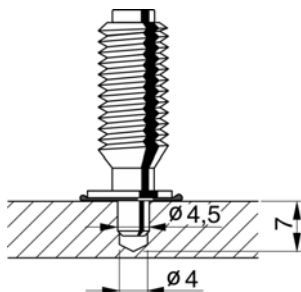


Figure 2. Sketch of X-BT fastening

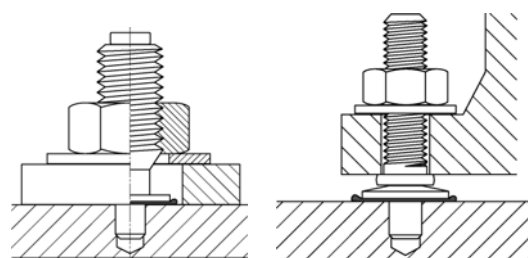


Figure 3. Fastening details (left M10/W10, right M6/W6)

The X-BT threaded fasteners are covered by international approvals issued by GL (Germanischer Lloyd), DNV (Det Norske Veritas), ABS (American Bureau of Shipping), LR (Lloyds Register), BV (Bureau Veritas), UL (Underwriter Laboratories) and ICC-ES (International Code Council). These approvals include the use of the specific step shank drill TX-BT 4/7, the powder-actuated tool DX 351-BT(G) and the 6.8/M brown precision cartridge. All these components build the Hilti X-BT direct fastening system.

2 Fatigue classification of structural steel with Hilti X-BT threaded fasteners

The effect of powder-actuated fasteners on the fatigue strength of structural steel was experimentally investigated in the 1980-ties by *Seeger* and *Melber* [5]. About 1'000 constant amplitude fatigue tests were performed with steel coupons into which Hilti powder-actuated fasteners were driven. Compared with welded studs the effect of the powder-actuated fasteners on the fatigue strength of the structural steel is less pronounced. In 1999 the detail category 90 in compliance with the Eurocode 3 was determined by *Seeger* [6, 3].

The good-natured behaviour of powder-actuated fasteners was explained with the development of beneficial circumferential compressive residual stresses as a result of the driving process. The blunt-tip X-BT fasteners are driven in a pre-drilled hole, which differs from conventional powder-actuated fastenings. Therefore, it was necessary to investigate the effect of X-BT fasteners on the fatigue strength in a supplementary experimental test program.

2.1 Experimental test program

About 180 constant amplitude fatigue tests were performed with steel coupons, Figure 5. The following photos show pictures from the test equipment used in the laboratory EMPA (Swiss Federal Laboratories for Materials Testing and Research).

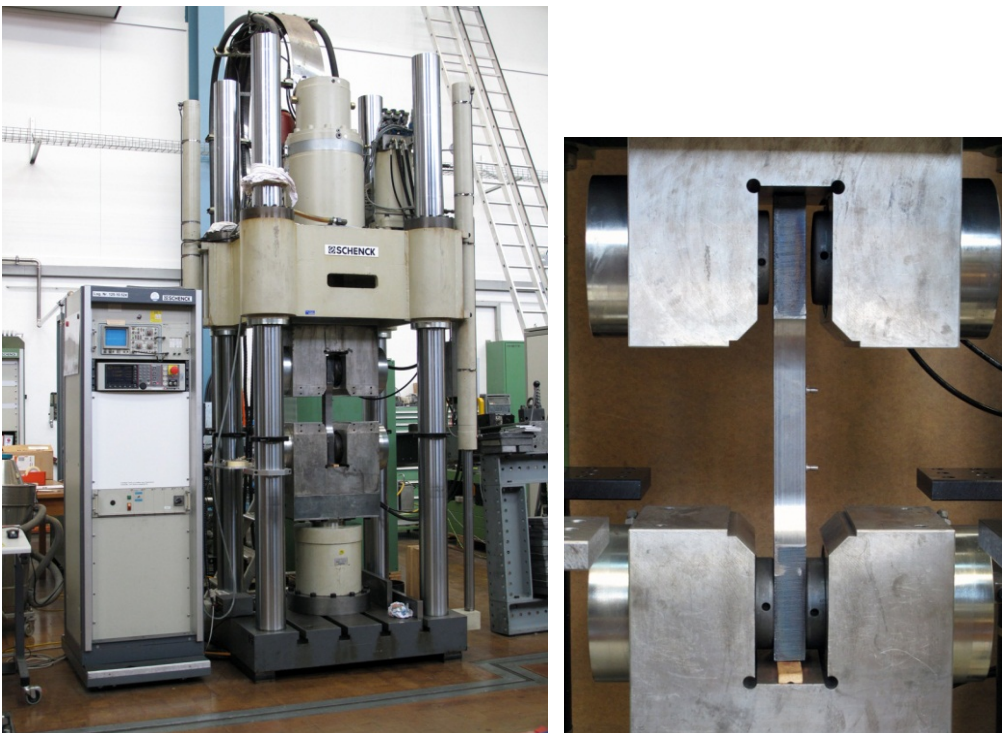


Figure 4. EMPA 1'000 kN test engine and clamping of coupons [7]

In total 19 test series were performed varying the following parameters:

- 4 different steel grades: S235JR, S355J2, S460M, S460G4+M
- 3 different plate thickness: 8, 20 and 40 mm
- 3 different stress ratios: $R = +0.5, +0.1, -1.0$
- 3 different installation conditions: correctly installed, installed and pulled-out, pre-drilled hole without fasteners

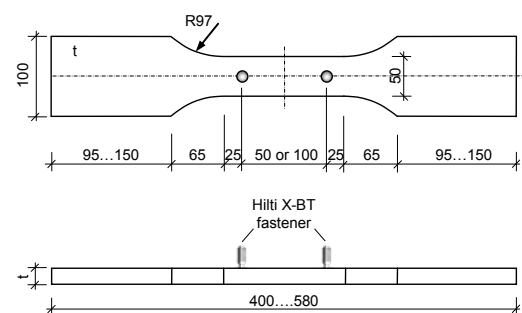


Figure 5. Geometry of coupon

The materials S235JR and S355J2 cover the range of non-alloyed structural steels according to EN 10025-2. In addition the grades S460M and S460G4+M cover thermo mechanically rolled fine-grain steels¹ according to EN 10025-4 and EN 10225.

The minimum plate thickness for the use of X-BT fasteners is 8 mm. Tests with thicker steels have been performed in order to investigate the thickness effect on the fatigue strength.

Besides the installation condition “perfectly installed”, also imperfect conditions have been included into the test program in order to cover the following situations:

- a) Fasteners were erroneously driven at wrong location and have been removed by pulling them out of the base material with a tension tester².
- b) Holes were drilled erroneously and no fasteners were driven into these holes.

The tests were carried out with a pulsation force ΔF at a constant stress ratio R ($R = F_{min} / F_{max}$). As high strength S460 fine grain steel was also used in the test program, it was possible to perform tests with $R = 0.5$ with stress ranges $\Delta\sigma$ up to 240 N/mm².

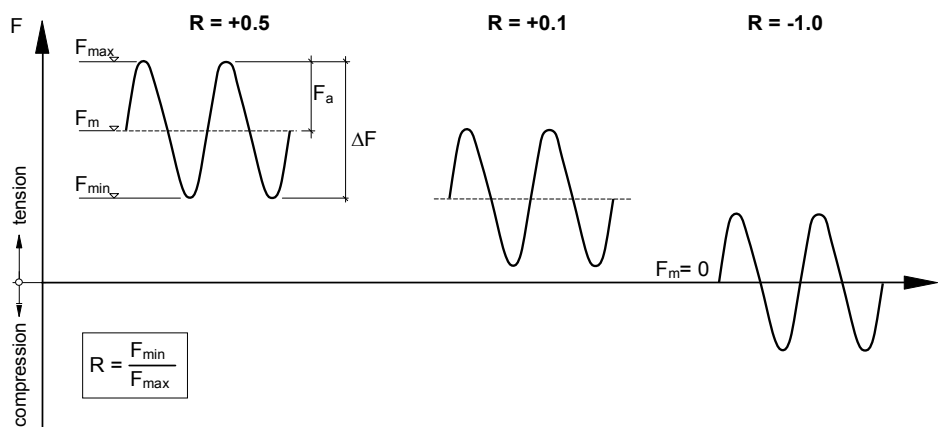


Figure 6. Constant amplitude load protocol and stress ratio R

¹ also referred to as TMCP steels

² Instead of pulling the fastener from the base metal, the fastener shank can also be cut using an angle grinder. When cutting the stud, any damage of the surface of the parent steel must be avoided.

2.2 Test results

2.2.1 Failure behaviour and discussion

As expected the samples typically failed in the cross section with the X-BT fasteners by crack initiation starting either in the vicinity of the stud or from the bottom of the pre-drilled hole. The following photos show typical examples of fractured samples.



Figure 7. Example of fractured coupon

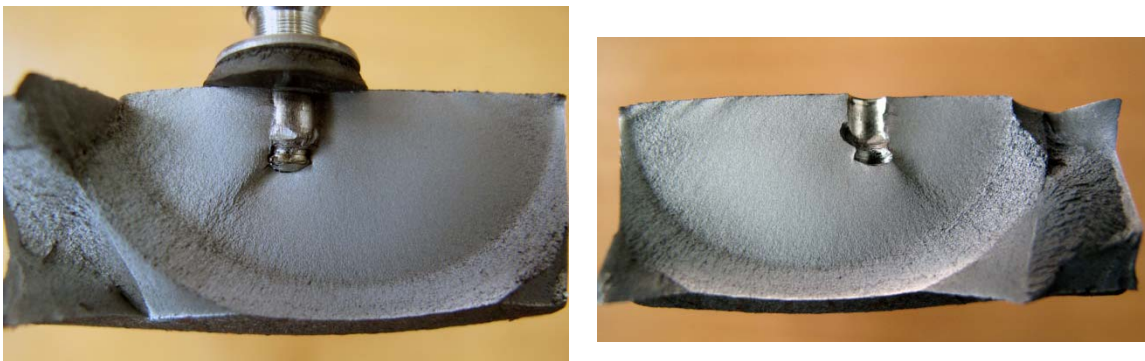


Figure 8. Example of cross sectional fracture area ($t = 20 \text{ mm}$)

The effect of the different test parameters on the fatigue strength is summarized as follows:

- In general no significant material effect was observed. The fatigue strength of the lower strength grades S235 was on a similar level than of the higher strength fine grain material.
- No size effect was concluded from the test results. A comparison test series with steel from one and the same heat but with different plate thickness (20 mm and 40 mm) did not show a reduced fatigue strength for the thicker base material.
- As expected the fatigue strength increases with reduction of the stress ratio R . Interestingly, for the series with $R = -1$, the fatigue failure was shifted from the cross section with the X-BT fastener to other geometrical notches (e.g. the curved transition) of the coupon. Consequently, fatigue failure of that series was not controlled by the presence of the X-BT fastener.
- The investigation of the installation conditions did not show, that one of the conditions represents a clear lower boundary for the fatigue resistance. The influence turned out to be in the range of about 10 % which lies in the typical scatter band of fatigue tests.

A more detailed discussion and comparison of the different parameters on the fatigue strength is given in [8].

2.2.2 Statistical evaluation in compliance with Eurocode 3 [8]

Based on the described observations the statistical evaluation of the fatigue tests was done with virtually all tests together [8]. Only the tests with $R = -1$, for which the failure was not controlled by the X-BT fastener, were excluded from the joint evaluation.

In keeping with the statistical requirements of the Eurocode 3, EN 1993-1-9:2005 [9] the fatigue resistance $\Delta\sigma_c$ is defined as the value at $2 \cdot 10^6$ load cycles that results from a 95% probability of survival ($P_{0.95\%}$) of the logarithm of the number of load cycles N with a confidence interval from the average of 75 %. The following figure, taken from [8], shows the fundamental concept of the statistical evaluation.

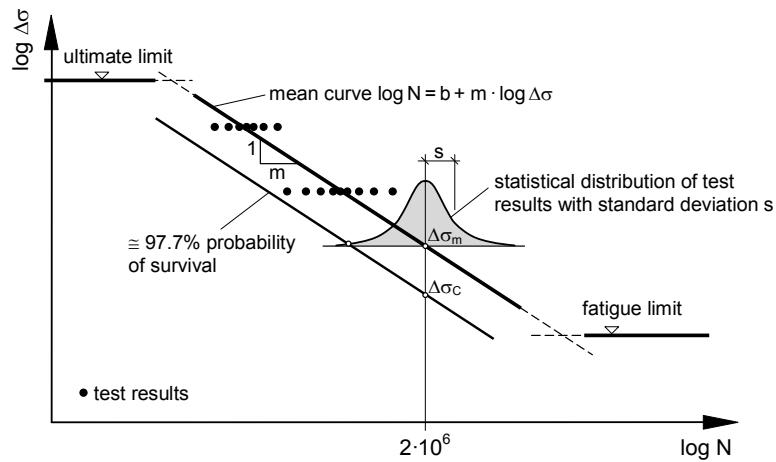


Figure 9. Statistical evaluation according to Eurocode 3 [8]

The statistical evaluation of [8] resulted into the following recommendations for the classification of the constructional detail “Structural steel base material with the Hilti powder-actuated fastener X-BT”.

Table 1. Recommendation of fatigue detail category according to EN 1993-1-9:2005 [8, 1]

Detail category	Constructional detail	Description	Requirements
90		Hilti X-BT powder-actuated fasteners with pre-drilled hole in structural steel base material. Imperfect fastener installations as e.g. pulled-out fasteners or pre-drilled holes without fasteners are covered.	$\Delta\sigma$ to be calculated by the gross cross-section. Installation, static loading and spacing of fasteners only in accordance with the requirements of the Hilti X-BT threaded fastener specification [1] Plate thickness $t \geq 8$ mm Edge distance ≥ 15 mm
100 $m = 5$			

Category 90 corresponds with a standard category according to Table 7.1 of EN 1993-1-9 (slope $m = 3$ for cycles $N \leq 5$ million cycles and slope $m = 5$ for $N > 5$ million cycles). Category 100 ($m = 5$) – with a constant slope $m = 5$ for $N \leq 100$ million cycles – represents a possible, alternate option in compliance with the Eurocode 3. The latter is recommended in case of low amplitude high cycle fatigue loading. When using a fatigue assessment procedure based on a linear damage accumulation a mixture of both categories is not allowed.

The structural steel grades S235 up to S460 according to EN 10025-2, EN 10025-3, EN 10025-4 and EN 10225 are covered. These grades include thermo mechanically rolled fine grain steels.

The following chart shows a summary of all test data including the fatigue classification in keeping with the Eurocode 3.

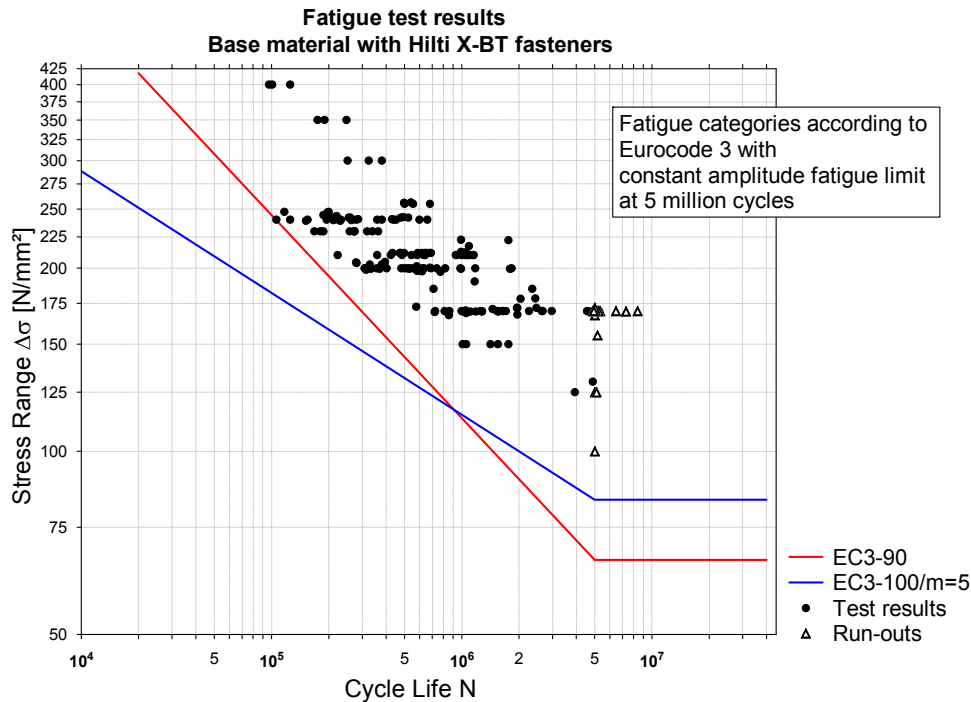


Figure 10. Test data compared with fatigue recommendation according to Eurocode 3 [8, 1]

2.3 Approved fatigue categories by GL (Germanischer Lloyd) and DNV (Det Norske Veritas)

Internationally, different fatigue design standards are in place in the different industries (e.g. bridge design, off-shore structures or shipbuilding). Though varying in the detail, their fundamental concept is very similar. The fatigue details are classified often into welded and non-welded details, which are allocated to fatigue design $\Delta\sigma$ -N curves. These usually refer to a 95 % or 97.7 % probability of survival. ABS [10] offers a survey of the internationally used fatigue design standards.

Towers for wind turbines as well as the machinery for the wind turbines often are approved by classification societies like GL (Germanischer Lloyd) or DNV (Det Norske Veritas). Both classification societies recently also approved the fatigue category for the constructional detail “Structural steel base material with Hilti powder-actuated fastener X-BT”, see Table 2.

Table 2. Approved categories by GL and DNV

Classification Society	Hilti Type Approval Certificate	Fatigue standard	Detail category	Plate thickness	Thickness effect
GL	12272-10HH [12]	EC 3, EN 1993-1-9 [9]	90	8 mm ≤ t ≤ 60 mm	No. k _s = 1
DNV	S-6751 [13]	DNV RP-C203 [11]	C2	t ≥ 8 mm	for t ≥ 25 mm k = 0.15

Notes on GL Type Approval:

In order to allow clear use of the design category, GL proposed only to use the standard category 90 and omit the alternative option 100 with m = 5. GL also limited the use to the thickness range typically used in steel towers of wind turbines (t ≤ 60 mm). In case thicker plates are exceptionally used, acceptance is possible based on case specific consideration.

Note on DNV Type Approval:

Differing from the provisions in EN 1993-1-9 [9], the DNV fatigue standard DNV-RP-C203 requires the consideration of the size effect (coefficient k = 0.15) for the detail category independent from the constructional detail. Therefore, for compliant design with DNV-RP-C203 a thickness effect is considered for thickness t ≥ 25 mm.

The fatigue strength curves are mathematically described by the following formula:

$$\log N = \log \bar{a} - m \cdot \log \Delta\sigma$$

The parameters m and $\log \bar{a}$ of the fatigue curves are summarized in the following tables 3 & 4. Table 5 gives also a comparison of the stress ranges $\Delta\sigma$ for selected numbers of cycles and Figure 11 shows a graph with test data and the approved fatigue categories.

Table 3. Parameters of GL approved fatigue curve 90 according to EN 1993-1-9

Number of load cycles	m	$\log \bar{a}$
$N \leq 5 \cdot 10^6$	3	12.164
$5 \cdot 10^6 \leq N \leq 10^8$	5	15.807

Table 4. Parameters of DNV approved fatigue curve C2 according to DNV-RP-C203

Number of load cycles	m	$\log \bar{a}$
$N \leq 10^7$	3	12.301
$10^7 \leq N \leq 10^8$	5	15.835

Table 5. Comparison of stress ranges

Number of load cycles N	Stress range $\Delta\sigma$ [N/mm ²]	
	GL EC3 - 90	DNV C2
$1 \cdot 10^5$	244.3	271.4
$1 \cdot 10^6$	113.4	126.0
$2 \cdot 10^6$	90.0	100.0
$5 \cdot 10^6$	66.3	73.7
$1 \cdot 10^7$	57.7	58.5
$1 \cdot 10^8$	36.4 ^{*)}	36.9

^{*)} corresponds with cut-off limit

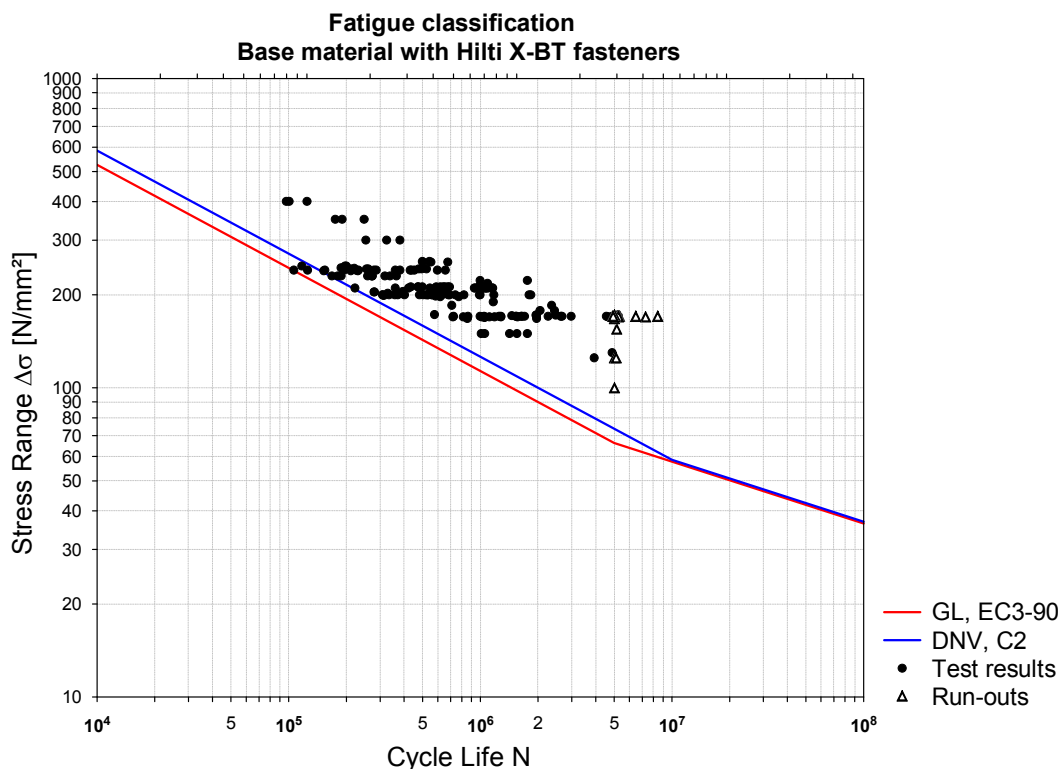


Figure 11. Test data compared with approved GL and DNV fatigue categories

3 Robustness verification of X-BT fasteners concerning dynamic loading

Towers for wind turbines are subjected to continuous dynamic wind loading. Therefore, the X-BT fasteners itself have to be robust against the effect of dynamic loading. All relevant aspects have been experimentally investigated. The results of these investigations proved the suitability of the X-BT fasteners on dynamically loaded steel structures like towers for wind turbines, ships or off-shore platforms.

In the following potential concerns related with dynamic loading are stated and a brief response is provided addressing the topic. Furthermore, reference is provided to more detailed literature:

Question 1 deals with a concern when the X-BT fastener itself is subjected to varying load:

Question 1: Does the anchorage of the X-BT fastener work loose, when subjected to varying tension loads?

Response:

No, the X-BT fasteners do not work loose over time. The anchorage of X-BT is also not detrimentally affected by dynamic pre-loading.

Fatigue tests with fasteners loaded in tension have been performed. In all tests the fatigue failure was controlled by fracture of the fastener material. Pullout of fasteners never occurred [3, 14].

Recently a test program was performed to verify X-BT fasteners to resist seismic loads. Fasteners were cyclically loaded in tension with an upper load of more than double the recommended working load of the X-BT. This upper test load was applied 10'000 times. After these cycles the residual pullout strength of the X-BT fasteners was determined and compared with control tension tests of fasteners, which were not pre-loaded. No difference in the pullout load was observed [14].

The explanation of this robust behaviour is the anchorage mechanism, which relies pre-dominantly on friction welding between the fastener shank and the base material [1].

Questions 2 and 3 deal with the effect of base metal stress on the pullout strength of the X-BT fasteners:

Question 2: What is the effect of a static tension stress in the base material on the pullout strength of the X-BT fastener?

Response:

The effect of tension stresses in the base metal on the pullout strength is small and conservatively covered by the safety factors³.

When loading the base steel up to 70 % of its yield strength, the pullout strength of X-BT fasteners still amounts to about 80 % of the pullout strength in non-stressed material. If the steel is even loaded up to its yield strength, the anchorage of the X-BT fasteners still remains intact and still amounts to about 35 % of the pullout strength from non-stressed material [15].

Question 3: What is the effect of dynamic base metal stress on the pullout strength of the X-BT fasteners? Do the fasteners work loose?

Response:

Cyclic loading of the base metal in the range and beyond its characteristic fatigue strength has only a negligible effect on the residual pullout load of the fastener. The X-BT fastener don't work loose over time, the anchorage remains intact.

A steel beam, in which X-BT fasteners were driven into the web as well as the tension and compression flange, was dynamically loaded resulting into harmonic bending of the section. Loading and frequency were selected such that the section was stressed beyond its characteristic fatigue strength [1, 16].

³ In keeping with the approval requirements given in AC70 [17] and issued by ICC-ES (International Code Council – Evaluation Service) the global safety factor between the characteristic pullout strength and the recommended tension load amounts to 3.5

4 Verification of fastenings made to cast iron with spheroidal graphite

Components made from cast iron with spheroidal graphite are typically used in the nacelle of wind towers. The preferred grade is EN-GJS-400-18LT according to EN 1563 with a minimum ultimate strength of 400 N/mm² (for thickness $t \leq 30$ mm), a minimum fracture strain A of 18 % and with impact toughness properties suitable for use in cold temperatures. The use of cast iron with spheroidal graphite allows economical production of complex machinery parts combined with ductile material behaviour.

The presence of spherical graphite is required to allow the casting process. Figure 12 shows a representative example of a microsection of cast iron EN-GJS-400-18LT. The distribution of the spheroidal graphite in the ferritic matrix is clearly visible.

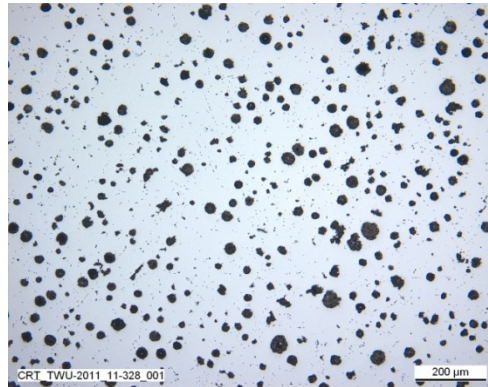


Figure 12. Microsection of cast iron EN-GJS-400-18LT:
Spheroidal graphite embedded in ferritic matrix

In order to investigate the effect of the cast iron base material on the performance of X-BT fasteners a comprehensive test program was run. The scope of the program included the following experimental investigations [18, 19]:

- Static pullout tests
- Static shear and bending tests
- Tension fatigue tests
- Tests to cover the effect of the edge distance
- Tests to cover the effect of the cast iron surface

An independent evaluation of the tests was made by *Kuhlmann & Günther* [20] from the University of Stuttgart. The recommended loads for X-BT fasteners driven into cast iron are given in the following Table 6.

Table 6. Recommended loads for X-BT fasteners

Loading direction	Recommended loads
Tension	$N_{rec} = 0.5$ kN (115 lbs)
Shear	$V_{rec} = 0.75$ kN (170 lbs)
Bending	$M_{rec} = 8.2$ Nm (6 ftlbs)

The cast iron needs to meet the following specification. Carbon content and microstructure is typical for EN-GJS-400-18LT used in the nacelle of wind towers.

Table 7. Requirements of spheroidal graphite cast iron base material

Subject	Requirements
Cast iron	Spheroidal graphite cast iron according to EN 1563
Strength class	EN-GJS-400 to EN-GJS-600 according to EN 1563
Chemical analysis and amount of carbon	3.3 - 4.0 mass percentage
Microstructure	Form IV to VI (spherical) according to EN ISO 945-1:2010 Minimum size 7 according to Figure 4 of EN ISO 945-1:2010
Material thickness	$t \geq 20$ mm

Compared with the performance of X-BT fasteners in unalloyed structural steel (see Figure 1 and [1]), the recommended load values are smaller due to the presence of the graphite in the cast iron. As with unalloyed structural steel reliable anchorage of the X-BT fastener is also caused by predominantly friction welding between the fastener shank and the ferritic or perlitic matrix of the cast iron. However, the presence of the graphite reduces the effective contact area, which explains the reduction of the pullout strength.

Furthermore, the recommended loads cover the effect of dynamic loading on the fastener. Tension fatigue tests were performed to investigate the robustness of the anchorage of the X-BT fastener in cast iron, see Figure 13 and 14.

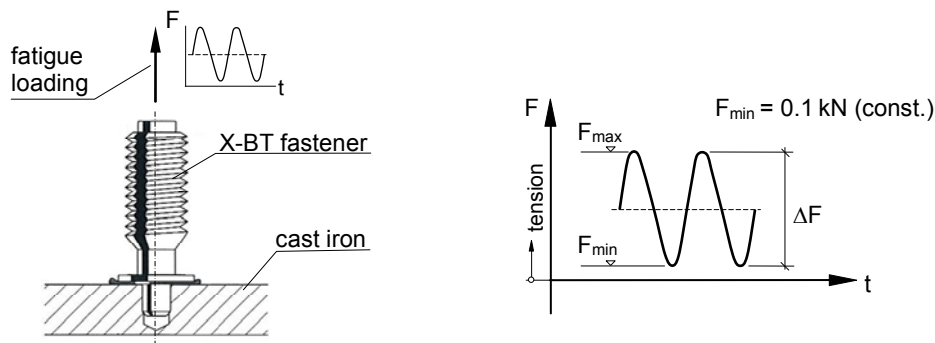


Figure 13. Principle sketch of cyclic tension tests



Figure 14. Servo-hydraulic test setup for tension fatigue tests

Conclusions from the cyclic tension tests:

- The anchorage of the X-BT does not work loose. In none of the tests pull-out of the fastener from the cast iron was the controlling mode of failure.
- Failure was controlled by fatigue fracture of the stainless stud material. The fractures occurred at upper loads significantly beyond the recommended tension load of 0.5 kN.

- For final verification and with respect to the reported design life of wind towers, two fatigue tests were performed with an upper load of 1.0 kN (which is double the recommended tension load) and a target number of 200 million load cycles.
- Both long run samples passed the test without any damage, neither to the fastener material nor to the anchorage. Residual static pullout tests of these two samples resulted in a pullout strength beyond 5 kN.
- The test results clearly verify reliable X-BT fastenings to cast iron EN-GJS-400-18LT used in the nacelle of wind towers.

Figure 15 shows a graph of the fatigue test results performed with the fastener X-BT M8-15-6 SN12-R. The load-level of the run-outs is by far beyond the recommended working load of 0.5 kN, especially see the two run-outs at 200 million load cycles with an upper load of 1.0 kN.

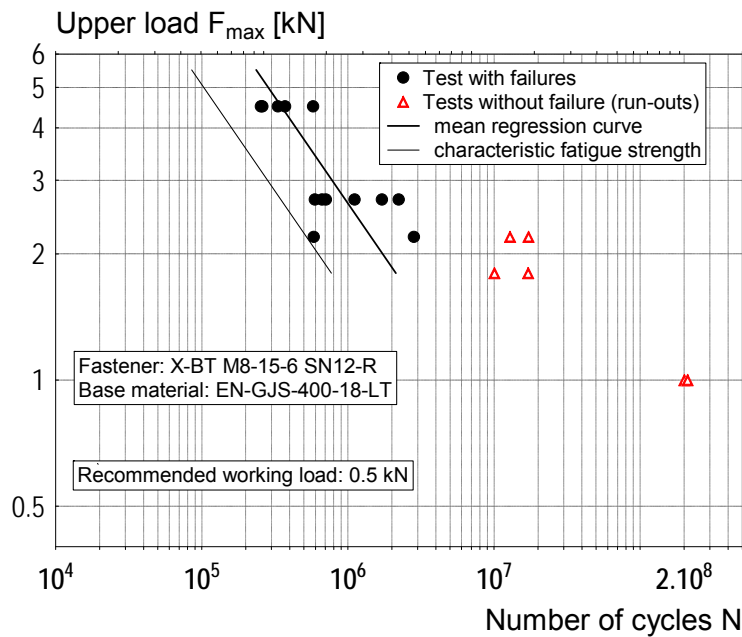


Figure 15. Results of cyclic tension tests

It is further planned to add the use of X-BT fasteners on cast iron components into the X-BT Type Approvals issued by GL [12] and DNV [13].

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