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Fatigue Assessment of High-Strength Bolts with Very Large Diameters in Substructures for Offshore Wind Turbines

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ABSTRACT

Bolted connections in support structures for offshore wind turbines need to be thoroughly designed against fatigue damage. However, experimental validation of applicable fatigue curves for bolts with large diameters is limited. In this paper appropriate design methods are described. Results of experimental fatigue tests on high-strength bolts of size M36 are presented, including a quantification of the effect of different zinc coatings and the validation of relevant design S-N curves. The experimental results are further used for validation and discussion of first calculation results with a numerical fatigue calculation method, based on the notch-strain approach.

KEY WORDS: high-strength bolts; ring-flange connections; fatigue; experimental testing; hot-dip galvanized, notch-strain concept.

INTRODUCTION

Bolted ring-flanges are widely used in support structures for offshore wind turbines for the connection between tower segments or between tower and sub-structures such as jackets, tripods or even floating structures. Moreover, ring-flange connections may also be applied as alternative to grouted joints for the conjunction between transition piece and monopile foundations, cf. Fig.1. For this application until today grouted joints, which are established by filling the annulus between monopile and slightly larger transition piece with a high-strength grout material, are the predominately used design solution. This connection, well established in the oil and gas sector to attach offshore platforms to driven pile foundations, allows to compensate inclinations from the ramming process of the pile. However, recently reported settlements of grouted joints on monopiles have revealed that existing experiences obtained from the oil and gas sector may not unconditionally be transferred to applications for offshore wind turbines. As a consequence, several wind farm projects with monopile foundation, e.g. the offshore wind park “Amrumbank West” in the German North Sea, are now planned and under construction with a design concept with bolted ring-flanges instead of grouted joints, cf. Gollub at al. (2014).

Bolts in wind turbines are subjected to high cyclic loads with considerable numbers of load cycles and variable amplitudes. Due to the high notch effect of the thread, bolts are decidedly susceptible to fatigue damage. Thus, it is essential that bolts in ring-flange connections are preloaded with high forces in order to reduce fatigue loads on the bolts. For protection against corrosion the bolts are commonly hot-dip galvanized. The zinc coating, however, affects the fatigue strength of the bolts.

Ring-flange connections in wind turbines are usually executed with prestressed, high-strength bolt assemblies (HV-sets) with large diameters of M36 and bigger. The magnitude of the acting loads at the bottom of the tower of large and powerful offshore turbines usually requires the application of very large bolt diameters M64 or M72. This applies even more for the connection level at the bottom of the transition piece on a monopile. In constructional engineering the application of such bolt dimension takes place almost exclusively in the emerging wind energy sector. Consequently, even though applicable design standards do not explicitly exclude their application on larger diameters, the experimental validation of relevant fatigue properties is mostly limited to smaller dimensions.

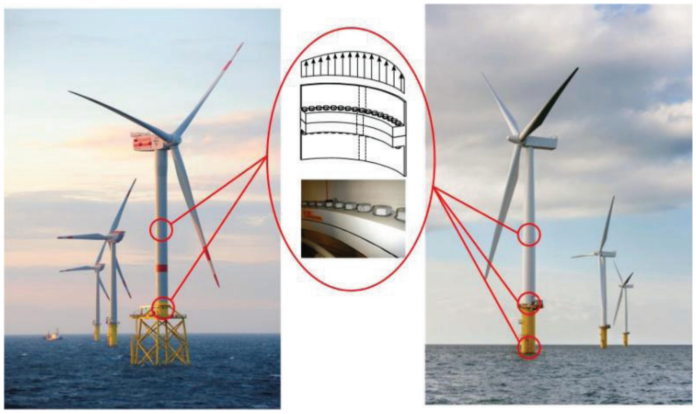

Fig.1. Potential locations of ring-flange connections in steel support structures for offshore wind turbines with jacket foundation (left) and monopile foundation (right)
©Pictures: DOTI (left), EON (centre, bottom), RWE (right)

For bolts with large diameters the experimental prediction of the fatigue behaviour under a realistic load level is a demanding and time consuming task because of the high loads and the large numbers of required specimens for appropriate statistical evaluation. Hence, the effect of the zinc coating on the fatigue strength of large-size bolts is still under investigation. Furthermore, until now applicable S-N curves, which can be used for verification with the nominal stress approach, are only experimentally validated on few statistically secured fatigue test data of bolts with large diameters. The corresponding S-N curve in European design standard EN 1993-1-9 had initially not been validated for bolt diameters larger than M36. With the objective of extending the scope of validation Schaumann & Marten (2009) have performed comprehensive fatigue tests on normal temperature hot-dip galvanized bolts of diameter M48. The results have confirmed the relevant detail category 50 of the standard in the region of the fatigue limit level as well as in the high cycle fatigue range. However, due to limitations of the testing facility the tests were conducted under a reduced mean stress level compared to the normative preload. This presumably led to an overestimation of the fatigue strength in the high cycle fatigue range. Thus, Marten (2009) recommends to perform future fatigue tests of large size bolts under representative mean load level.

Within the frame work of a joint research project (IGF-Project No. 486 ZN) the fatigue strength of large-size, high-strength bolts, under consideration of the boundary layer effect of the zinc coating, is experimentally investigated. Moreover, the research aims for the development of an analytical fatigue calculation method, based on the notch strain approach, which may be applied for further investigations instead of expensive experimental tests.

FATIGUE DESIGN OF BOLTED RING-FLANGE CONNECTIONS

Design Concept

Bolts in ring-flange connections in offshore wind turbines need to be thoroughly designed against fatigue damage. To facilitate the design process, dimensioning is performed using a simplified approach where only one bolt is assessed on the isolated, maximally loaded segment of the flange, cf. Fig.2.

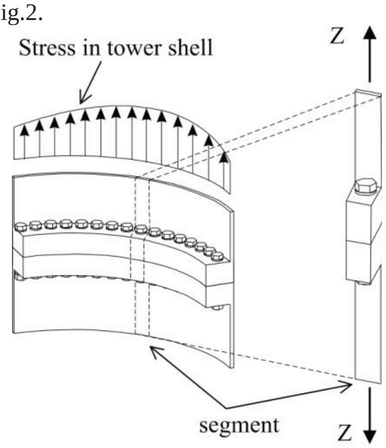

Fig.2. Segment approach for the design of bolted ring-flange connections, Seidel (2001)

In order to reduce the fatigue loads, which are acting on the bolt inside the flange package, the bolts need to be preloaded. For flange connections in wind turbines it is recommend (e.g. GL (2012)) to apply a nominal preload F_p according to Eq.1 corresponding to 70% of the 0.2%-yield stress $R_{p0.2\%}$ of the high-strength bolt material. Preloading of very large-size bolts is commonly achieved with the torque method, where the nut is tightened with a hydraulic wrench until a defined torque moment is reached.

$$F_p = 0.7 \cdot R_{p0,2\%} \cdot A_{sp} \tag{1}$$

where:

F_p nominal preload

$R_{p0,2\%}$ 0,2%-yield stress

A_{sp} tensile stress area of the bolt threat

The preloading and the eccentric geometry of the connection leads to a non-linear relation between tension force in the tower shell segment Z and resulting nominal bolt stress S (F_s+ M_s) (following denoted as transfer function). Due to the non-linearity of the transfer function between tower force and bolt stress, knowledge about the mean level of the outer stress ranges is essential. Thus, for design a load spectrum of the tower loads at connection level in the form of a three dimensional Markov-Matrix must be at hand. After evaluating the resulting bolt stress ranges with the corresponding transfer function, the endurable number of load cycles is calculated, based on the nominal stress approach, with an appropriate S-N-curve. Calculation of total lifetime fatigue damage D and verification is then performed using Miner's rule (Eq. 2).

$$D = \sum_{i=1}^{m} \frac{n_i}{N_{F,i}} \leq 1.0 \tag{2}$$

S-N Curves

Even though, the eccentricity between tower wall and bolts leads to certain bending stresses, the loading conditions of bolts inside a ring-flange are characterized by predominating axial stresses. Thus, S-N curves based on experiments under pure axial loading are used for design. Relevant S-N curves for axially loaded bolts are given in European design standard for civil engineering EN 1993-1-9 (EC 3) and in the internationally renowned VDI guideline 2230 (VDI 2230), which has been especially developed for high duty bolted joints in mechanical engineering, cf. Fig. 3. In contrast to EC 3, all S-N curves are plotted in stress amplitudes S_a and not stress ranges ΔS ($\Delta S = 2S_a$). As it can be seen in Fig. 3 the fatigue strength of hot-dip galvanized HV-Sets (rolled before heat treatment) is regulated more conservatively in EC 3 than in VDI 2230. Albeit higher bolt diameters exceed the range of experimental validation, the two regulations do not define a corresponding limitation. However, a reduction of the fatigue strength for higher bolt diameters is considered in both regulations. For the depicted range between diameter M36 and M72 the reduction according to VDI 2230 is considerably lower than according to EC 3.

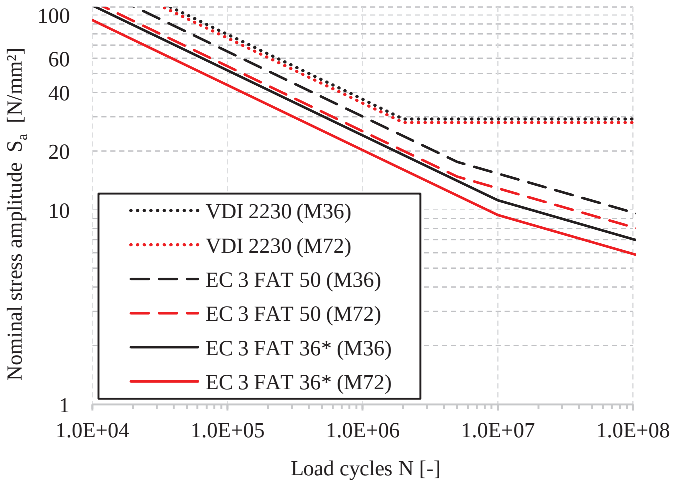

Fig.3. S-N curves according to EC 3 und VDI 2230 (2014) for hot-dip galvanized HV-Sets (rolled before heat treatment) for bolt diameters M36 and M72

Fatigue experiments on high-strength bolts M48, performed by Schaumann & Marten (2009), have shown that pure bending loading conditions lead to a more favorable fatigue behavior than pure axial loading. Thus, the application of S-N-curves for pure axial loading is conservative. The actual fatigue strength of the bolts inside the flange connection under combined axial and bending loading can be estimated somewhere in between the S-N-curves for pure axial und pure bending loading. However, the amount of the bending influence depends on the flange geometry and thus on the individual structure. Hence, the beneficial effect on the fatigue strength caused by combined loading is difficult to consider in the design.

Even though bending effects are neglected in the S-N curve, they have to be considered when assessing the fatigue loading of the bolts. According to the current design practice, EC 3 detail category FAT 50 may only be applied for verification if bending stresses are considered in the load determination. If bending stresses are neglected, detail category FAT 36* according to EC3 has to be applied, cf. GL (2012). Moreover, it has to be noted that according to GL (2012) the consideration of a threshold value, as shown in Fig. 3 in the curves of VDI 2230 at $2 \cdot 10^6$ load cycles, may not be considered in the fatigue design of offshore wind turbine structures.

Design analysis of ring-flange connections on monopile foundations

Generally, the design of ring-flange connections on monopile foundations, applied as alternative to grouted joints, is equal to conventional flange connections. However, new constructional and design challenges arise. One of the main advantages of grouted joints is that they enable to correct inclinations of the monopile. This facilitates the driving process on site because higher inclinations are tolerable. Since within a ring-flange connection inclinations cannot be compensated, it must be assured that pile inclinations are limited to a technically tolerable magnitude, thus potentially leading to higher building costs. Moreover, it needs to be considered that, in compliance with necessary quality requirements, flanges cannot be welded offshore to the already installed monopile. Consequently, it has to be secured by high technical efforts that the driving impact on the flange is limited and the flange atop of the monopile is not severely damaged during installation of the pile. Due to the resulting requirements of the flange design, the manufacturing becomes more sophisticated.

Conventionally, the lowest station for a flange connection in an offshore wind turbine structure is at the working platform at the interface between tower and foundation structure, located above splash zone level, cf. Fig.1 (left). If used in a monopile foundation the lowest flange station can be considerably lower, approximately at about mean seawater level (MSL). Consequently proper sealing against the ingress of seawater becomes necessary. Moreover, the increase of the lever arm of aerodynamic turbine and tower loads and the addition of wave loads lead to an aggravation of loading conditions.

In a feasibility study the authors analysed design aspects for the application of ring-flange connections on monopile foundations. The investigations were carried out based on the results of a representative Ultimate Limit State (ULS) and Fatigue Limit State (FLS) load calculation of a generic offshore wind turbine model with monopile foundation, cf. Schaumann et al. (2013). The analysed ring-flange is located at MSL. Dimensioning the ring-flange in the ULS based on the plastic failure modes defined by Petersen (1997) and Seidel (2001), design is feasible if at least bolts of diameter M64 are used. The application of bolts M72 leads to a reduction of the required bolt number of about 30, from 130 (M64) to 100 (M72), while maintaining a utilization ratio of about 90 %.

For design in the FLS an appropriate approach for the approximation of the non-linear bolt force transfer function is essential, cf. Fig. 4. Since in fatigue design not the absolute magnitude of the bolt stress but the range between upper and lower bound of the occurring stress cycles is the decisive factor, the slope of the transfer function with respect to the increase of bolt stresses from the initial pre-stress level is the design driving parameter. As shown in Fig.4 preloading of the connection leads to a much gentler slope at the beginning of the transfer function, effectively reducing the fatigue loads of the bolt.

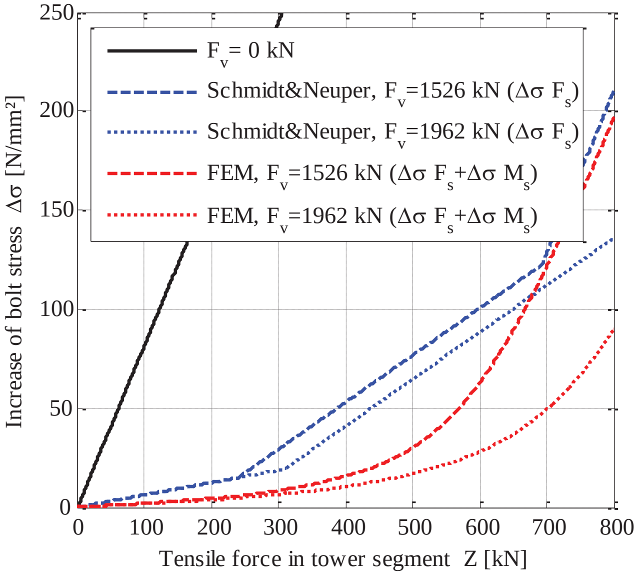

Fig.4. Non-linear bolt stress transfer functions for a flange connection with bolts M72

In order to take into account possible preload losses, in the fatigue verification the preloading force F_v may be considered with a maximum value of 90 % of the nominal preload F_p, cf. GL (2012). Additionally, in the design study the preload level has been further reduced to $F_v = 0.7 \cdot F_p$ for comparison. Simplified analytical approaches for determination of the bolt stress transfer function as the method according to Schmidt & Neuper (1997) solely consider axial stresses ($\Delta\sigma\ F_s$) of the bolt and disregard the stresses from the bending moment caused by the eccentric load application ($\Delta\sigma\ M_s$). Thus, the reduced detail category 36* according to EC3 has to be applied for verification. The application of the finite element method leads to a considerably more accurate approximation of the actual bolt stress transfer function, cf. Seidel (2001). Furthermore, it enables the consideration of bending stresses and thus the application of EC3 detail category 50. The results of the corresponding fatigue damage calculations for the analysed ring-flange connection with bolts M72 are given in Table 1.

Table 1. Results of damage calculation for bolts M72 acc. to Eq. 2

	Schmidt & Neuper		FEM	
Preload	1962 kN ($0.9 \cdot F_p$)	1526 kN ($0.7 \cdot F_p$)	1962 kN ($0.9 \cdot F_p$)	1526 kN ($0.7 \cdot F_p$)
Damage	D = 0.13	D = 1.13	D < 0.01	D < 0.01

Due to the conservative approximation of the transfer function and the lower detail category, the application of the simplified approach according to Schmidt & Neuper leads to considerably higher calculated damage values. Under consideration of a reduced preload level the verification is not fulfilled. When applying the transfer functions calculated with FEM the damage values can be significantly reduces because of the small slope at the beginning. Nevertheless, it must be considered that in the FE-model perfectly plane flange conditions are assumed and unfavourable effects from flange imperfections remain unconsidered. The severe effect of imperfections on the transmission behaviour between tower loading and bolt force has been demonstrated by Feldmann et al. (2011). Since imperfections increase with bigger dimensions, this becomes of even higher importance for flanges at lower connection levels. Thus, the application of transfer functions, calculated with FEM, is only permitted if unfavourable imperfections in a realistic order of magnitude are considered in the model, cf. GL (2012). This, however, leads to significantly increased modelling efforts. As a simplified approach in this study initial flange gapping has been considered in terms of an inclined contact surface in the FE-model, cf. Fig. 5. The comparison of the resulting transfer functions with inclinations between 0.0° and 0.5° emphasize the unfavourable effect on the bolt loading, cf. Fig. 6. For practical application magnitude of imperfections and modelling approach has to be assessed individually for the specific geometry and manufacturing conditions. Generally, it is crucial to limit flange imperfections according to requirements given in the applicable standards and guidelines (e.g. GL 2012).

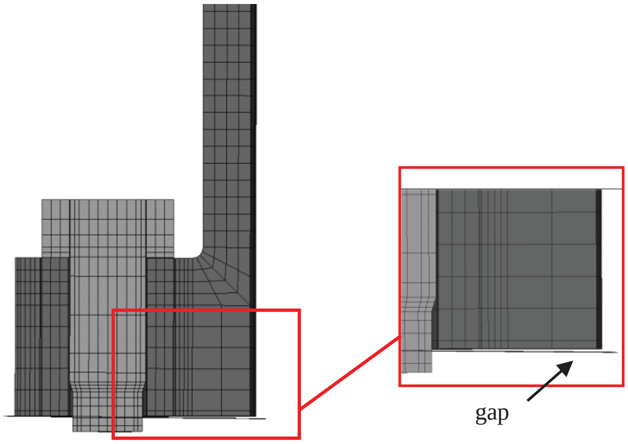

Fig.5. Modelling of flange gapping in FE-model with bolt M72

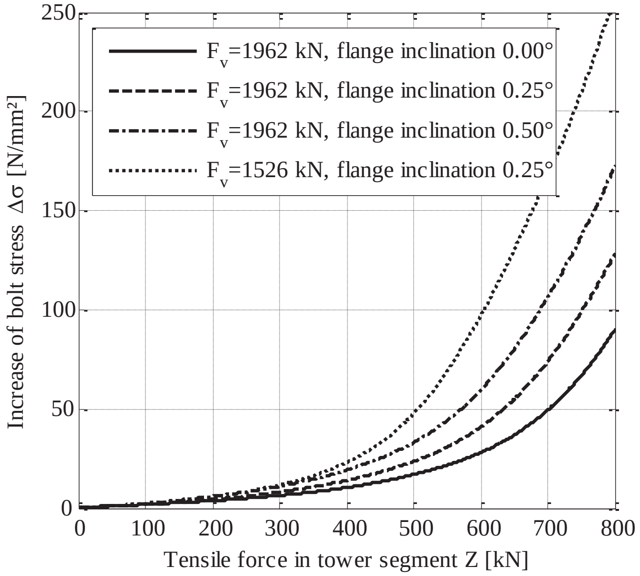

Fig.6. Non-liner bolt stress transfer functions for a flange connection with bolts M72 under consideration of flange gaping (FEM)

EXPERIMENTAL INVESTIGATIONS

Test set-up and procedure

Experimental investigations were performed on large-size HV-sets (including bolt, nut and two shims) of diameter M36 with geometrical properties in accordance with EN 14399-4. All tested bolts were produced in one manufacturing batch and rolled before heat treatment. Tests were performed under pure axial loading with constant amplitude and a constant tensile mean stress of $S_m = 0.7 \cdot R_{p,0.2\%}$, corresponding to the nominal preload for M36 bolt sets (515 kN). The mean stress was established directly by the testing machine. In order to investigate the influence of the zinc coating, applied for corrosion protection, test series were performed for three different boundary layer configurations:

- Black bolts (no coating) (B)
- Normal temperature hot-dip galvanized (~460 °C) (NT)
- High temperature hot-dip galvanized (~550 °C) (HT)

Tests were carried out in a high frequency pulsator (1MN MOT), enabling a testing frequency of about 50 Hz, cf. Fig. 7. Adaption of specimens to the testing machine as well as statistical evaluation of results was performed in accordance with DIN 969 / ISO 3800. To enable the determination of full S-N curves, first the endurance limit was statistically estimated using the stair-case method developed by Dixon & Mood (1948). Afterwards, the slope of the S-N curves was determined by testing at two defined load horizons in the high cycle fatigue regime. Test runs ended either by rupture of the bolts or after reaching the defined “run-out” limit of at least $5 \cdot 10^6$ load cycles. In total more than 100 tests were run.

Fig.7. Test set-up for high-strength bolt-sets M36 under pure axial loading in a high frequency pulsator

Test results of high-strength bolts M36

The test results, presented in Fig. 8, show a clear effect of the zinc coating on the fatigue strength for hot-dip galvanized bolts in the region of the endurance limit as well as in the high cycle fatigue range. For normal temperature hot-dip galvanized bolts (NT) the statistically estimated endurance limit is reduced about 21 % compared to the black, uncoated bolts (B). For high temperature coating (HT) a reduction of about 19 % is obtained. However, the statistical evaluation has shown a considerable overlap of the scatter bands of the NT and HT series. Thus, no significant measurable deviation can be supposed. It is concluded that for normal and high temperature hot-dip galvanized bolts a comparable decrease of fatigue strength can be assumed. Generally, this is in accordance with the suggestion of VDI 2230 which recommends to reduce the endurance limit of hot-dip galvanized bolts (HT and NT) by 20 %.

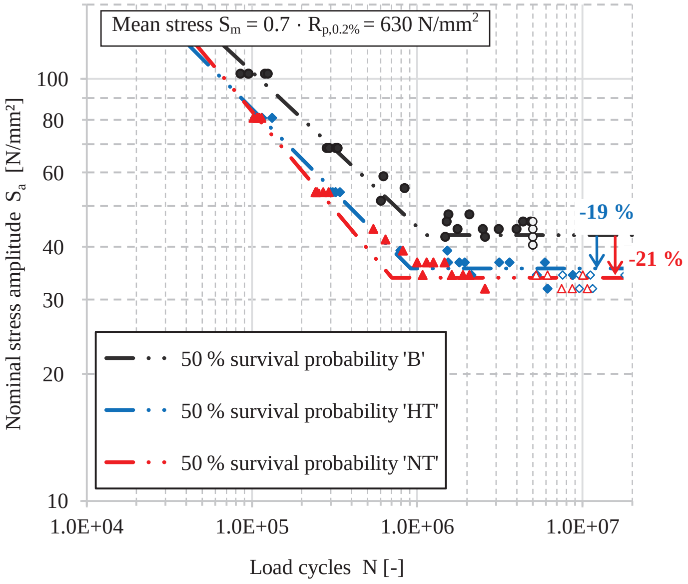

Fig.8. Fatigue test results for high-strength bolt sets M36 with different boundary layer configuration (filled marker (●): failure of specimen; empty marker (○): run-out)

Fig. 9 and Fig. 10 show the comparison of test results with the relevant normative S-N curves from EC 3 (plotted in stress amplitudes $S_a = \Delta S/2$) and VDI 2230 under consideration of the thickness reduction for bolt diameter M36. The depicted curves of VDI 2230 consider the recommended reduction for the specific geometry of HV-Sets (endurance limit reduced by 10 %) as well as the reduction for hot-dip galvanized bolts (endurance limit additionally reduced by 20 % in Fig. 10). The detail catalogue of EC 3 principally does not consider a distinction between coated and uncoated bolts. Consequently, according to the standard all bolts need to be classified in detail category FAT 50, regardless of the effect of the zinc coating. However, GL Guideline for Offshore Wind Turbines GL (2012) allows classifying black, uncoated bolts in EC 3 detail category FAT 71. Thus, in Fig. 9 both detail categories are represented for comparison.

As stated in the guideline the design relevant S-N curve of VDI 2230 is given with a survival probability of 99 %. For both, uncoated and galvanized bolts, the majority of failures of test specimens in the high cycle fatigue range lie shortly below the fatigue curve of VDI 2230. Consequently, it can be assessed that the fatigue strength is overestimated to a certain degree by the given pathway of the S-N curve. Furthermore, according to the guideline the fatigue strength given for the high cycle fatigue regime may not indiscriminately be applied for a service life fatigue verification with a load spectrum of more than one load group, as done in the verification of ring-flange connections. The assumption of the endurance limit of the guideline is on the safe side if the recommended reduction of 10 % for HV-sets is considered, as depicted here. It is noted that this recommendation has just been included in the latest revision of VDI 2230 (2014). Without consideration of the recommended reduction, the endurance limits for black and hot-dip galvanized M36 HV-Sets, obtained by the test results, are overestimated.

The EC 3 S-N curves are stated for a survival probability of approximately 97.7 % of the fatigue strength at $N = 2 \cdot 10^6$ load cycles. As expected, all test results lie above the fatigue curve of corresponding detail category FAT 50, thus confirming its safe practical applicability. Moreover, the results justify the application of detail category FAT 71 for bolts without thermal coating, as recommended in GL (2012). In the high cycle fatigue range the results show a good but safe approximation to the EC 3 fatigue curves. After the determined endurance limit is reached the applied stair case method assumes a horizontal progression of the S-N curve. However, this has to be interpreted as a theoretical approach in order to enable the production of representative results with manageable experimental effort. In order to investigate the actual presence of a threshold value of the fatigue strength or alternatively to determine the slope of the S-N curve in the very high cycle fatigue regime, very cost and time consuming test series are required, cf. Steppeler (2014). However, the presented test results clearly show a considerable brake of the S-N curve slope with substantial more shallow progression in the region of the determined endurance limit than in the EC 3 curves. Consequently, the pathway of the S-N curves according to EC 3 leads to a very conservative design estimation in the region of higher load cycle numbers.

The findings are generally in accordance with the results of Schaumann & Marten (2009) for axially loaded, normal temperature galvanized bolts M48. Moreover, lower bearable load cycle numbers obtained for the higher load levels, confirm the previously stated assumption that the high mean stress level affects the fatigue strength in the high cycle fatigue regime.

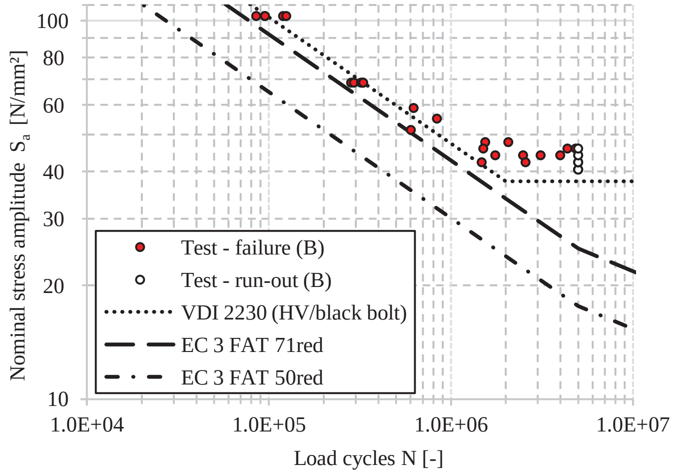

Fig.9. Comparison between test results of black bolts (B) M36 and relevant normative S-N curves

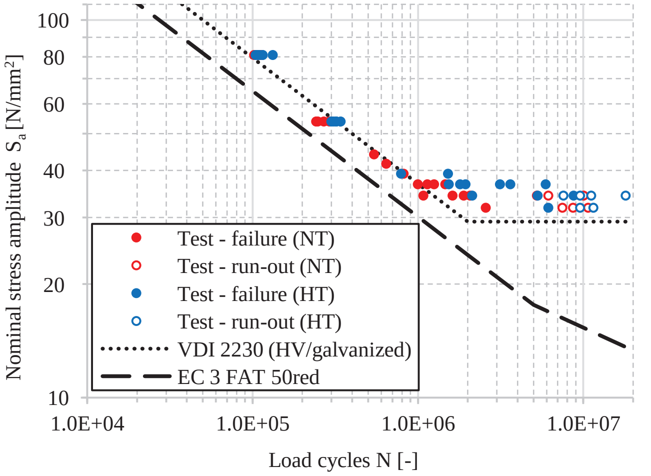

Fig.10. Comparison between test results of hot-dip galvanized bolts (NT & HT) M36 and relevant normative S-N curves

Outlook on experimental investigations on high-strength bolts M64

Based on the results of the comprehensive test series on bolts M36 further tests will be performed on bolts M64 in order to extend the scope of experimental validation to very large bolt diameters. Due to the high required load levels fatigue testing of bolts with such dimensions is a challenging task and, to the knowledge of the authors, no equivalent test data is currently publically available.

To enable testing under representative mean load level, test will be performed in a high-strength servo-hydraulic testing machine, located at the Leibniz University Hannover. Compared to the high frequency pulsator used in the M36 test series, possible loading frequencies will be considerably lower and the test duration for the single bolts will be significantly higher. Thus, only a smaller number of specimens can be tested with acceptable time and cost effort.

As in the presented M36 test series different boundary layer configurations will be analysed. However, because of the given possibility of Liquid Metal Assisted Cracking (LMAC) high temperature galvanization may not be used for very large-size bolts such as M64. Moreover, the results for bolts M36 have shown that the effect on the fatigue strength is comparable for both coating processes. Thus, for bolts M64 only black and normal temperature galvanized bolts will be tested. To limit the test duration, the tests will primarily be performed in the high cycle fatigue range with expected load cycles until rupture between $N = \sim 5 \cdot 10^4$ and $N = \sim 1 \cdot 10^6$. Under consideration of the previously obtained results the tests will enable a good assessment of the influence of an increased diameter on the fatigue characteristics of high-strength bolts.

ANALYTICAL FATIGUE CALCULATION

The fatigue life until crack initiation can be analysed with the local notch strain approach. A corresponding assessment method can be applied in order to further investigate relevant parameters which may influence the fatigue behaviour of large-size bolts.

First calculations have been performed using cyclic material data of representative high-strength bolt materials given in Boller & Seeger (1988) and Schneider (2010). A corresponding non-linear cyclic material behaviour is implemented into a finite element model according to the relation defined by Ramberg & Osgood (1943). Using a two dimensional, axial symmetric FE model according to Marten (2009), the relation between outer loading and maximal local strain in the first load bearing turn of the thread is calculated, cf. Fig. 11. For determination of the cyclic hysteresis under repetitive loading Masing behaviour is considered.

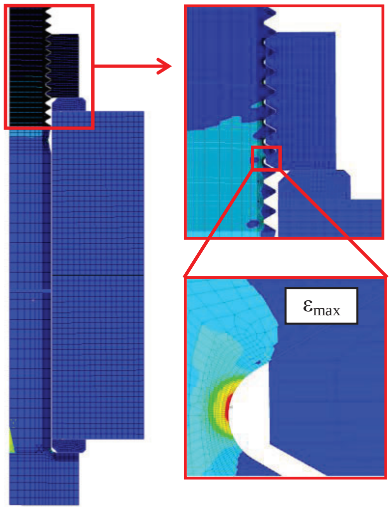

Fig.11. Calculation of local strain ε in bolt thread with 2D axial symmetric model

In common application of the notch strain approach, the path of the initial load application in the local hysteresis is calculated considering the cyclic stress-strain relation of the material. However, in the case of pre stressed bolts this cannot be regarded as an accurate assumption because in both, practical application and experiment, preloading is achieved under monotonic conditions. Thus, following the recommendation from Schneider (2010), the pathway of the first load application is calculated more realistically with monotonic material behaviour. As shown in Fig.12 this leads to a higher mean stress level of the local hysteresis which affects the calculated damage. Stress and strain amplitude remain identical for both approaches.

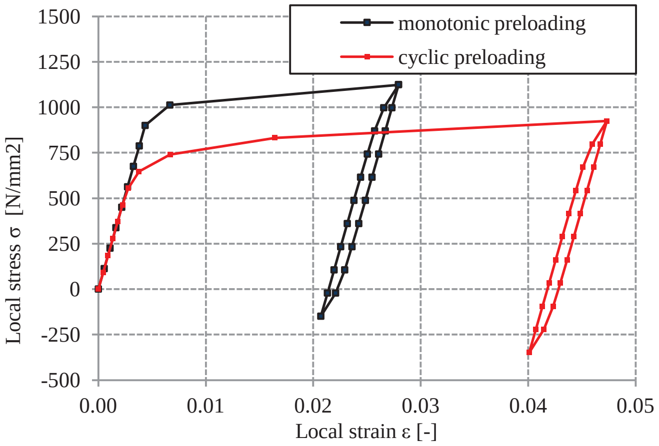

Fig.12. Local hysteresis with monotonic and cyclic pathway of initial load application

Evaluating the pathway of the local hysteresis, damage calculation can be performed using the strain woehler curve of the examined material. The influence of the mean stress is considered with the damage parameter P_{SWT} according to Eq.3.

$$P_{SWT} = \sqrt{(\sigma_a + \sigma_m) + \varepsilon_a \cdot E} \qquad (3)$$

where:

σ_a	local stress amplitude
σ_m	local mean stress
ε_a	local strain amplitude
E	Youngs-modulus

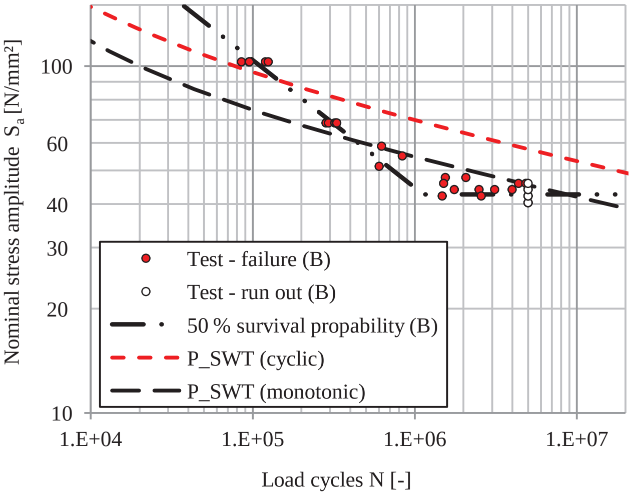

Fig.13. Comparison of S-N curves calculated with the notch strain approach (until crack initiation) and test results of black bolts M36

The comparison of the S-N curves calculated with the notch strain approach for bolts M36 and the experimental results for black bolts, given in Fig. 13, show a much better compliance when calculated under consideration of a monotonic preloading path. However, using the P_{SWT} damage parameter the bearable load cycles in the region of the endurance limit are still overestimated to a certain degree. It is expected that a better compliance can be achieved when using the more complex damage parameter P_J by Vormwald (1989), which is based on a more accurate fracture mechanical approach. In the high cycle fatigue range the calculated S-N curves lie below the experimental results because here fatigue life is calculated only until crack initiation. The additional load cycles until rupture can be calculated with the crack propagation method, cf. FKM-Guideline (2006).

The presented calculations are performed with published cyclic material data of a 36CrB4 which differs from the actual material of the tested bolts 32CrB4. Cyclic material properties of the actual bolt material are experimentally determined within the joint research project at the Institute for Material Sciences, TU Darmstadt. Moreover, cyclic relaxation effects which occur under high mean strains are assessed. These will be included in the model, to evaluate the influence of the material properties and include relaxation effects, which especially influence the fatigue life at high load levels, cf. Schneider (2010).

When calculating the fatigue live of galvanized bolts the effect of the boundary layer, which leads to a reduction of fatigue life, has to be considered in particular. The mechanical phenomena, leading to the reduction are intensively investigated at TU Darmstadt. The accurate incorporation of the complex processes in analytical or numerical calculations is still subject of current research. A simplified but manageable approach may be the "thin-layer" model by Seeger & Heuler (1984), which was generally developed for consideration of boundary layers which do not substantially affect the stiffness of the multi-material system.

CONCLUSIONS

High-strength, hot-dip galvanized bolts are used in ring-flange connections in towers of offshore wind turbines. Ring-flanges may also be a promising design alternative to grouted joints to connect transition piece and tower to monopile foundations. Under consideration of representative offshore loads it has been demonstrated that design in ULS and FLS is generally feasible for this application if bolts with very large diameters M64 or M72 are used. However, applicable S-N curves of relevant regulations are not validated for such diameters. A considerably more economic fatigue design is possible if load transfer functions calculated with FEM are used. However, it is prerequisite to limit and, moreover, accurately consider flange imperfections when assessing the load transfer. To prevent bolts from fatigue damage preloading with high forces is essential. Since the mean load affects the bolts fatigue strength, it is advisable to perform fatigue tests under a representative mean load level. The high required loads complicate fatigue testing, especially for large diameters.

In comprehensive test series on high-strength bolts M36 it is shown that the galvanization has a substantial effect on the bolts' fatigue life. However, the results confirmed a safe but rather conservative design assumption of the S-N curve of the applicable design standard EN 1993-1-9. Based on the obtained results a reduced test series will be performed on bolts M64 to validate existing fatigue assumptions for very large diameters. For further investigations of fatigue relevant parameters, an analytical assessment method, based on the notch strain approach, is developed. First results show an acceptable approximation to the experimental results, if an initial preloading path with monotonic material behaviour is considered. Further stages of the model will include the application of a more accurate damage parameter, incorporation the actual material data of the tested bolts and consider the boundary layer effect of the zinc coating.

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