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A review of fatigue performance of bolted connections in offshore wind turbines

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Abstract

Flanged bolted connections are used in offshore wind turbines to connect the monopile to the transition piece, and the transition piece to the tower. Forces and moments generated by the effects of winds, waves and currents subject these connections to variable amplitude cyclic loads. In the harsh marine offshore environment areas such as bolt threads are vulnerable to fatigue cracking and failure. Their structural integrity and life are influenced by coatings, lubricants, bolt size, design and tension, manufacturing tolerances and flange contact.

This paper presents a review of the main challenges for fatigue life assessment of M72 bolted connections used in offshore wind turbines **to connect the monopile to the transition piece,** and the factors affecting the fatigue performance. Existing standards and guidelines along with different fatigue assessment methods presented in the literature are discussed in terms of their suitability for fatigue life assessment of M72 bolted connections for offshore wind turbines. One of the key challenges in fatigue life assessment of large scale bolts (e.g. M72) is the lack of experimental data points from which fatigue design curves can be derived. Recommendations are made for how to improve the current best practice for fatigue assessment of large scale bolted connections in the offshore wind industry and potential areas for further investigation are proposed for future research.

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Keywords: bolted connection; preload; fatigue; transition piece

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1. Introduction

The study of how bolting assemblies are influenced by fatigue are presented below. In offshore engineering, bolted connections are employed in a very large number of structural members. These connections may look simple on the surface level, but are complex assembles with varying geometric and fatigue properties which needs to be properly

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accounted for in order to provide a clear picture of their useful life in service. An introduction into fatigue and methods by which fatigue strength can be quantified are examined. Also presented are the standards currently used to govern design, installation and operational life of bolted connections offshore. Several studies on bolted connections on wind turbines have been done, and they have provided useful trends in the behavior of these connections as well as multiple ideas on how they can be compared and analyzed.

Nomenclature

HV	Hochfest Vorgespannt
MPa	Mega Pascals
M	Bolt diameter in mm
Rp0.2	0.2 % plastic strain limit
S- N	Stress vs number of cycles
FAT 50	Fatigue category
W3	Cut threads
F1	Cold rolled threads with no following heat treatment like hot galvanising
µm	Micrometre
MCS	Monte Carlo Simulation technique
FORM	First-order reliability method

Standards

DNV OS J101	Design of Offshore Wind Turbine Structures
DNV RP C203	Recommended Practise: Fatigue design of offshore steel structures
VDI 2230	Systematic calculation of high duty bolted joints: Joints with one cylindrical bolt
BS 7608	Guide to fatigue design and assessment of steel products
EN 1993-1-9	Eurocode 3: Design of steel structures – Part 1-9: Fatigue
BS EN 14399-4	High-strength structural bolting assemblies for preloading Part 4: System HV — Hexagon bolt and nut assemblies

2. Bolted Connection Design

2.1. Bolt set design

Bolts are fasteners used to assemble two unthreaded components, in combination with a nut through the mating of threads. This assembly applies an axial clamping force. The Hochfest Vorgespannt (HV) bolt set, meaning high resistance bolts for pretension, is recommended in BS EN 14399-4. These bolts are Grade 10.9 indicating an ultimate tensile strength of 1,000MPa and yield strength of 900MPa. These are preloaded assemblies with thin nuts and short threads. These assemblies are sensitive to over-tightening during preload and, if this occurs, give no warning to failure by plastic deformation of the engaged thread of the bolt according to Steel Construction Institute (2008).

2.2. Nut design

As reported by Charlton and Vancouver (2011) to create this mating condition of the threads, the thread form is not identical to the bolt, nor is it of the same material, as it must deform upon tightening to distribute the loads over all the threads, not just the first few. A distance of two or more thread pitches from the nut face to the thread run-out is recommended to avoid the stress concentration due to poorly formed threads as explained by Eccles (2004).

2.3. Flange design

Achmus et al. (2013) explained that the L-shape of the bolted flanged connection displaces the bolt axis eccentrically to the line of force of the connection. Through experimental testing, it is found that loading bolts under pure axial has a reduced in fatigue strength when compared to combined axial and bending, but this has not yet been adequately quantified. For bolts bigger than M20, inclination of bolt support surface to bolt axis is limited to 2° as proven by Schwedler et al. (2018).

3. Installation

Russel (2017) wrote an article detailing that although grouted connections has been proven effective for offshore applications and it allows for inclinations in the ramming process of the monopile, errors in the DNV OS J101 standard lead to slippage of the transition piece down the monopiles within one year. This equation was later corrected. For bolted connections during the installation process elastic interaction usually occurs when tightening of one bolt alters the load on the adjacent bolts. Zhu et al. (2017) describes that this can cause bolts to lose about 98% of initial preload after bolt tightening of adjacent bolts. This behavior was found to be repeatable and can be considered predictable. Tightening processes used to install bolts include torque control method, combined method and direct tension indicator.

4. Loading Conditions

Bolted connections are subjected to preload and cyclic loads which results in high mean stress, high notch effect and surface slippage which leads to fatigue damage as indicated by Novoselac et al. (2014) Bolt tension varies with the change in the dimension of flange thickness, flange width and bolt diameter. Tafheem (2011) shows that bolt tension decreases with the increasing number of bolts. In bolted connections, the first engaged thread of the bolt is critical, and is subjected to the highest forces due to the condition that forces and moments in threaded region is not uniformly distributed. Charlton and Vancouver (2011) indicated that approximately one third of the load is taken up in the first thread; approximately three-quarters of the load are taken up in the first three threads; and, the first six threads take essentially the complete load.

Preload operates by creating a friction force between the parts it ensures that the joint stays tightly connected during application. Schaumann and Eichstädt (2016) explained that for large-size HV-sets the applicable preloading force corresponds to 70 % of the nominal 0.2 %-plastic strain limit Rp0.2 of the high-strength bolt material. Failure to tighten fastener assemblies up to their proper working loads accounts for over 75% of all fasteners failures according to Charlton and Vancouver (2011). Eccles (2019) indicated that insufficient tightening or loosening, exposes the bolt to stresses it is not designed to sustain which overcomes the clamp force acting between the joint faces. “A preloaded bolt in a typical joint sustains usually only around 5% (or less) of the applied loading (the remaining 95% reduces the clamp force acting on the joint).” Eccles (2004) also states that if a bolt is properly tightened it becomes highly resistant to fatigue loading. Shahani and Shakeri (2015) investigated the effect of preload on the fatigue life of bolts by producing a series of S-N curves for different levels of preload. The experimental results shows that the preload reduces the endurance limit of bolts by an amount proportional to the increase in the mean stress produced by the preload. However, beyond a significant mean stress, the endurance limit increases too.

5. S-N curves for bolts

In the bolted connection, the presence of eccentricity between the tower wall and bolts means that both bending and axial stresses exists in the assembly. Schaumann and Eichstädt (2015) explained that the fatigue strength of the bolt in the flange connection is then somewhere between the axial and bending fatigue strength results, with traditional pure axial curves being conservative. Axial stresses are predominant, and thus S-N curves based on experiments under pure axial loading are used for design. Schaumann and Eichstädt (2016) state that S- N curves in design standards for fatigue verification are only validated on smaller bolts, the fatigue characteristics of bolts with increased diameter has yet to be validated. Schaumann et al. (2010) had previously indicated that standards do not define a corresponding limitation of using the thickness correction equation although a reduction of the fatigue strength for higher bolt diameters is considered.

Schaumann and Eichstädt (2015) explained that the limitation to EN 1993-1-9 is that it does not consider a distinction between coated and uncoated bolts and all standard all bolts need to be classified in detail category FAT 50, regardless of the effect of the zinc coating. Lim (2017) indicated that in DNV RP C203 written by Der Norske Veritas (2016) it is unclear whether the bolt fatigue curves of W3 and F1 represent the fatigue capacity of preloaded bolts. Both regulations do not define the range of application regarding the thickness correction. Schaumann and Eichstädt (2018) indicated however, VDI 2230 is recommended for bolt diameters smaller than 40 mm. In case of EN 1993-1-9 the relevant S-N curve detail category 50 is not verified for bolt diameters larger than 36 mm, whereas both in DNVGL CP 203 and BS 7608 written by BSI (2015) the largest verified bolt diameter is M25. These three standards have the same equation for thickness correction, but there verified base curves differ for the same diameter bolt.

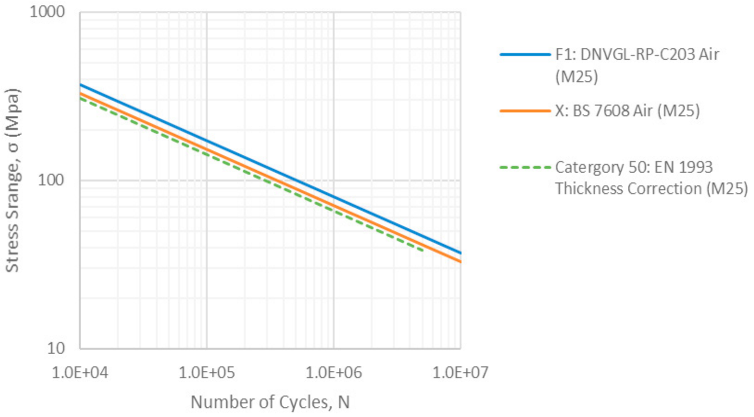

Figure 1: Comparison of S-N Curves for M25 Bolt in Air

As seen from Figure 1 the validated S-N curves for F1 (DNVGL RP C203), X (BS 7608) and Category 50 (EN 1993 with thickness correction from M30 to M25) in air all show variable fatigue strengths. The discrepancy between guidance given in these standards becomes more apparent if we apply them to bolt size M72 in air and with cathodic protection, Figure 2. The visualization of the difference in fatigue strength of the altered curves displays the impact on designs when considering bolted connections in wind turbines offshore.

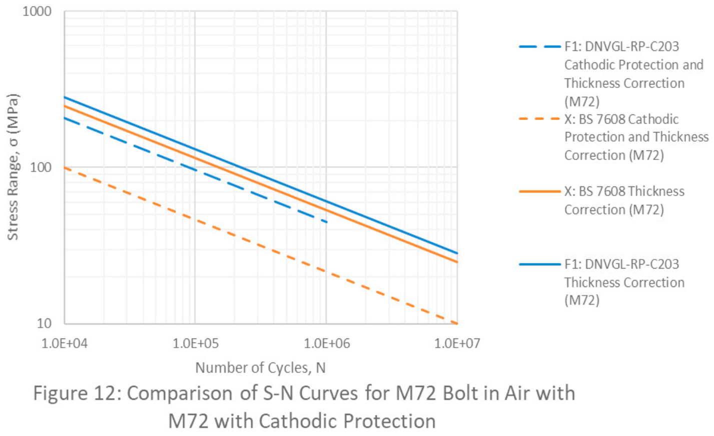

Figure 2: Comparison of S-N Curves for M72 bolt in air with M72 bolt with cathodic protection

6. Factors affecting fatigue of bolted connections

Fatigue is a process by which repetitive application of loads, even those well below yield strength of a material leads to an accumulation of damage. A crack can start at some existing defect, such as an inclusion in the metal, or at point of high stress, such as a notch, and slowly grow in length at each loading. It may take millions of load or stress cycles before the crack is actually detectable. As the length of the crack increases, the material remaining is placed under increasing stress because there is less area to sustain the loading. When the crack actually reaches a critical length it progresses all the way through the material resulting in complete failure as explained by Eccles (2004). The failure surface of a specimen under fatigue reveals “beach marks” which shows when the crack did not propagate for some the number of cycles, and then continued.

6.1. Location of bolt fatigue cracks

Fatigue failures of bolts typically occur in the three main areas of stress concentration as shown by Charlton and Vancouver (2011); see corresponding locations in Figure 3:

- 65% occur in the root of the first loaded thread (location 5)
- 20% in the thread run-out region (location 3)
- 15% occur in the head to shank radius (location 1)

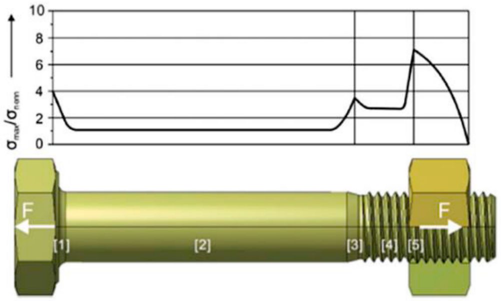

Figure 3: Critical Locations of Main Locations of Bolt Fatigue Failure from Eccles (2004).

6.2. Influences on fatigue strength

A bolt can fail via self-loosening, fatigue or overload, and the location of failure is usually concentrated in the area of highest stress described by Charlton and Vancouver (2011). The region of highest stress is inside the threads of the bolt. The bolt diameter influences the stress gradient inside the thread, where larger bolts have high stresses than smaller bolts for the same nominal stress. Eccles (2004) describes that the size effect on fatigue means the larger the part the lower the fatigue strength under the same stresses. This statistical size effect cannot be quantified according to Achmus et al. (2013). Achmus et al. (2013) further explained that thread pitch to bolt diameter ratio decreases as the diameter increases which also affects the stress gradient inside the bolt. Therefore different stress gradients for varying bolt diameters do not only result from the diameter but also from different elastic stress concentration factors. So the geometrical influence on the fatigue strength of bolts is not a pure size effect but a mixture of size and notch effect as Schaumann et al. (2010) explained.

Achmus et al. (2013) and Schaumann et al. (2010) explained that the microstructure of the bolt material is influenced by the manufacturing process, resulting in differing fatigue behavior. This effect cannot be quantified due to variable material and manufacturing process for different bolt diameters.

Surface finish of the bolt threads influence the fatigue life, where the smoother the surface, like threads that are rolled have a higher fatigue life than threads that have been cut indicated by Eccles (2004).

Bolts with threads rolled after heat treatment provides the compressive stresses at the thread roots, assisting in the prevention of crack initiation and significantly improving fatigue life of bolts. Eccles (2004) confirms this manufacturing process can double fatigue strength when compared to ground threads but it is more expensive, alternatively shot peening can be used. This can induce compressive stresses on large diameter bolts and improve fatigue strength. This is further affected as the thickness increases, and the residual stress at the boundary layer differs from the core material of the bolt as indicated by Achmus et al. (2013) and Schaumann et al. (2010).

Matsunari (2018) performed a study on the effect of curvature radius of the thread bottom and the pitch difference on fatigue strength for a size M16 bolt and nut. Using experiments to develop an S-N curve and finite element analysis, it was found that the initiation and propagation of crack are changed by introducing the pitch difference (i.e. the pitch of the nut is 15μm larger than the pitch of the bolt) of α=15 μm. Additionally, the fatigue life can be extended by increasing curvature radius of thread bottom, doubling the radius lead to two times the fatigue life and 30% larger fatigue limit than the normal bolt and nut dimensions. Eccles (2004) describes that with an increased root radius, the stress concentration at the root radius is reduced.

For protection against corrosion in the offshore the bolts are commonly hot-dip galvanized. Schaumann and Eichstädt (2015) explained that the zinc coating, however, reduces the fatigue strength of the bolts. Schaumann and Eichstädt (2015) conducted a study was on hot-dip galvanized bolts and tested the performance of black, normal temperature and high temperature galvanized M36 bolts. Schaumann and Eichstädt (2015) revealed that M36 bolts show a reduction of the endurance limit by about 20 % due to this coating. This effect on the fatigue strength of large-size bolts is still under investigation.

7. Fatigue assessment methods

Fatigue assessment is a methods are used to estimate the fatigue strength or endurance of a particular configuration or component. The fatigue performance of the bolted connection depends both on the material properties and also the configuration of the components in the joint Achmus et al. (2013) explained. For certain cases common fatigue assessment approaches need to be complimented by experimental tests to provide an economic design. Fatigue assessment methods use for bolted connections are listed below.

7.1. Nominal stress approach

Achmus et al. (2013) and Schaumann et al (2018) indicated that in EN 1993-1-9 (2005) where S-N curves for a specific structural detail is given and the nominal cross section is defined this method can be used to evaluate fatigue strength. Lim (2017) explained that the S-N approach does not distinguish between initiation and propagation, unlike fracture mechanics which assumes that a flaw exists and addresses propagation. This approach looks at average stress in bolt cross-section and does not consider local stress- strain state at the thread roots. Novoselac et al. (2014) explained that the bolted joint fatigue strength depends on notch effect which contains both stress concentration and strength reduction by notches.

7.2. Structural stress approach

This is the hot-spot approach and it considers local stress peaks in the stress calculations and not within the S-N curve. Local structural details, such as stress concentration factor can be calculated by parametric equations in DNV-OS-J101 (2013) or finite element analysis described by Achmus et al. (2013).

7.3. Notch stress approach

This approach considers notch effects within the stress calculation, modelling exact structural detail allows for calculation of stress peak at the notch surface. Achmus et al. (2013) indicated this method can be found in DNV-OS-J101 (2013) but is not yet standardized. Fatigue assessment based on notch stress follows the same procedure as the nominal stress approach, with consideration of local effective notch stress instead of global stress.

7.4. Notch strain approach

For this approach failure occurs at crack initiation and considers repetitive local yielding to modulate the crack. The Neuber rule of the notch is used to observe local deformations, and the stress-strain curve is being modelled to the Ramber–Osgood relation. Schaumann et al. (2018) explained that this is the way that maximum local deformation, the average stress, and the difference in notch stress is calculated. To evaluate a fatigue assessment comparable with previous methods, fracture mechanics is used with the results from this approach. Schaumann and Eichstädt (2015 and 2016) have successfully used this method in combination with non-linear finite element calculations as an analytical fatigue method for bolted connections of wind turbines.

7.5. Experimental Approach

Schaumann and Eichstädt (2015) explained that for flanged connections requiring large size bolts, there has been limited fatigue strength data that has been validated for bolts bigger than M36 in standards. For example EN 1993-1-9 has fatigue tested M36 bolts and offer a thickness correction equation for different size bolts. This same thickness equation is given in BS 7608 and DNVGL RP C203, but most importantly we must note that these three standards provide different initial validated S-N curves, for tested bolts, when compared to one another. Achmus et al. (2013) indicated that another reason true-scale fatigue tests are needed are to provide experimental data of structural detail fatigue performance to validate local fatigue assessment methods i.e. notch stress and notch strain approaches. For different size bolts, material and geometric properties are no consistent for these assemblies.

There are a few key points to take into consideration when fatigue testing bolts. These tests need to be performed using one manufacturer with the same material of full HV bolt set including bolt, nut and washers. It is unclear whether this was done in the validated S-N curve guidelines given in current standards. Experiments pertaining to the fatigue performance of large diameter bolts require representative load levels which is not only limited due to available test equipment, but expensive and time consuming to meet appropriate statistical evaluation of large specimen numbers required. Achmus et al. (2013) states that the influence of load frequency during experimental testing on fatigue strength of bolts is still under investigation.

7.6. Deterministic approach

Sadaphale and Wadadkar (2015) explained that identification of average nominal load ranges are done and the most damaging of these are selected and determines the nominal stress ranges. Each average stress range is calculated, by either S-N curves or damage fraction, using the associated number of cycles to failure. This is fed into the Miner's rule where the resulting total damage on the component is calculated to predict fatigue.

7.7. Probabilistic approach

For fatigue assessment, traditional methods define fatigue strength based on constant amplitude stressing. The probabilistic approach takes into account a damage accumulation law due to random loading encountered in practice. Using this method uncertain parameters like the environment, loading and structural response may be modelled to evaluate the fatigue failure probability of HV bolted connections as indicated by Sadaphale and Wadadkar (2015).

Schaumann et al. (2018) detailed that the partial factor method, which takes into account safety factors for scattering parameters such as wind loads, preload and geometric imperfections, was found to have insufficient data to convey these parameters as well as the reliability index. An alternative method is the reliability analysis, which computes the reliability index directly. This can be done using first-order reliability method (FORM) or Monte Carlo Simulation technique (MCS) and incorporating the statistics of the scattering parameters. Scattering parameters are modelled as stochastic variables when evaluating the limit state function. The MCS technique is found to be more accurate than FORM, having considered a representative sample size.

8 Conclusion

The structural integrity of the bolted flange connection is affected by fatigue loading which is influenced by environmental loads, material and geometry. Understanding how these high value assets fail is critical to the effective design, installation and operational life of offshore wind turbines. To account for the gaps in current standards for larger bolts e.g. M72, testing should occur to validate numerical and analytical models, as well as standards with suggested thickness adjustment.

Development of analytical and numerical analysis methods to account for the hot-dip galvanized layer, fabrication and installation tolerances of the bolt assembly and flange need to be accounted for. The effect for flange thickness on bolt tension is not currently captured and studies into this area should provide insight into efficiently designing these connections.

The main research and factors affecting bolted connections are presented in this study relating to geometry of connection, installation, loading conditions, S-N curve for bolts, influences on fatigue strength and fatigue assessment methods.

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