DOI: 10.1002/stco.202000060

Peter Schaumann, Manuela Böhm, Karsten Schürmann

Improvements in the fatigue design of support structures for offshore wind turbines

Extended keynote paper of Eurosteel 2021

This article provides an overview of the various support structures for offshore wind turbines and addresses the challenges that arise for the different design variants. First of all, the existing types of support structures are explained and their benefits and shortcomings discussed. Following that, the focus is on material fatigue and its analysis, which is of great importance due to the cyclic loading on the structures. A central topic of this article is the experimental evaluation of fatigue strength using large-scale test setups and state-of-the-art measurement methods. Critical and complex design details such as welds for extremely thick plates, tubular joints, grouted connections, large HV bolts and ring flanges are investigated to improve methods of analysis. Further, the new series of German standards (DIN 18088) for support structures for wind energy turbines and platforms is addressed. Finally, these topics are summarized and the importance of offshore wind energy for the transition to cleaner energy is emphasized.

Keywords offshore wind energy; support structures; fatigue strength; connections; welded steel joints; standardization

1 Introduction

The large-scale use of wind energy is one of the most promising sources of regenerative energy. The global availability of wind at virtually any time, the relatively low cost of operation and the high level of technical development ensure that wind energy is one of the most important electricity supply technologies worldwide. In the context of the European Green Deal, which states that the EU aims to become climate-neutral by 2050 [1], offshore wind energy will play a key role. To reach this goal it is estimated that approx. 450 GW of offshore wind capacity will be needed by 2050 [2]. Thus, the European installation rate needs to be significantly accelerated from 3 GW per year to more than 20 GW in the mid-2030s. This is a major challenge for the wind energy industry, since the planning and approval of offshore wind farms is a multidisciplinary, time-consuming process. In addition, changes to legislation in Germany, for example, have led to an economically volatile situation, as demand for production and installation capacity is continuously fluctuating.

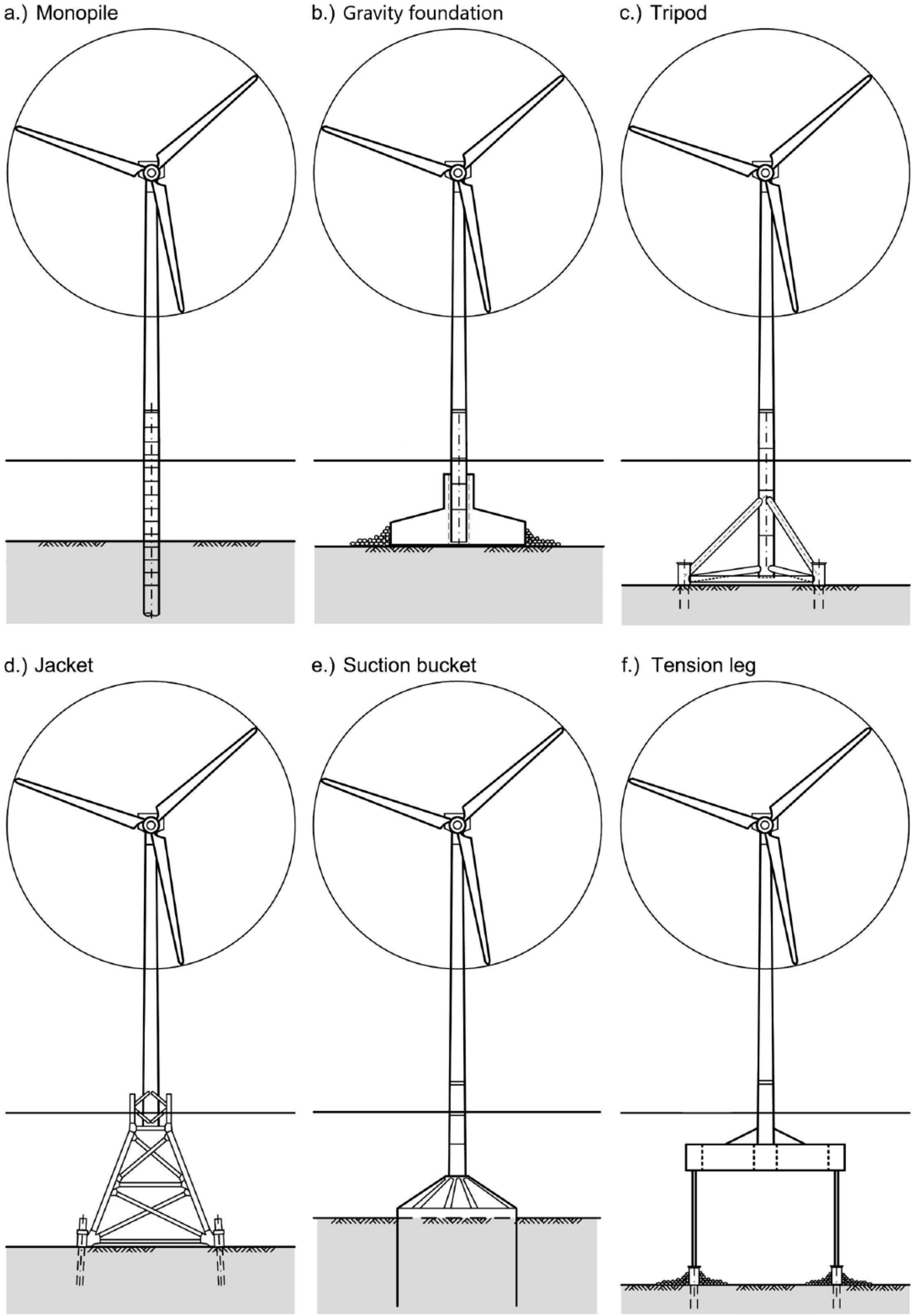
A further challenge, particularly for structural engineers, arises from the constant increase in turbine diameters and power outputs, which increases the loads on the support structures. Three analyses are crucial for support structures: the ultimate limit state for extreme loads from wind and waves, the fatigue strength under the cyclic loads from operation, wind and waves, and the resonance properties of the support structure. In recent years, the influence of corrosion on the fatigue strength has gained significance. For connections, efforts are being made to achieve water and air tightness through design measures, but in practice, corrosion is an issue. This problem should be taken into account in the future, e.g. when defining acceptable execution tolerances for ring flange connections. However, the turbines already installed show that, in particular, the fatigue strength of the connections is a very critical issue and not all observed effects are fully understood. Further research is required to establish the behaviour of the different connections (grouted, bolted or welded) under alternating loads. Based on these findings, normative regulations can be extended to provide more detail.

This article provides an overview of the design types of this technology and an important aspect of stability – the fatigue analysis. Some of the latest findings and developments in fatigue research are summarized in this article and some examples of large-scale test setups and state-of-the-art assessment methods are presented. Further, the new series of German standards, DIN 18088 [3], is introduced, which provides regulations for special details of support structures for wind energy converters.

2 Support structures

According to the current state of knowledge, the structural design of the support structure must be adapted to the specific requirements of each site; there is no universal solution. Hence, the different parameters that affect the design of these structures are considered on a case-by-case basis. Almost all support structures are made of steel. Towers for offshore wind energy turbines are also constructed as tubular steel towers, in contrast to towers for onshore turbines, which these days are often built using prestressed concrete. Three parameters essentially determine the design of a support structure: turbine size, water depth and soil conditions. The capacity of the turbine determines the mass distribution, the hub height and the tower base diameter. The water depth and the location

---



(source: Schaumann [5])

Fig. 1 Support structures design types for offshore wind turbines: a) monopile, b) gravity foundation, c) tripod, d) jacket, e) suction bucket, and f) tension leg

are critical for the loads from waves, ocean currents and any ice loads. The soil conditions have a particular effect on the length of the anchoring piles. Fig. 1 shows six types of support structures currently common. In the following, the benefits and limitations of the individual designs are briefly described. The numbers of substructures currently installed, categorized by type, are shown in Fig. 2.

The monopile (Fig. 1a, Fig. 3) is currently the type by far the most frequently built (see Fig. 2). The name of this construction method is derived from the fact that it has only one single steel pile. The largest monopiles reach diameters of up to 12 m and individual weights of almost 2500 t [6]. Although this type of structure requires a lot of material, the welding work has been automated to a high degree. In contrast to multi-pile solutions, which include jackets or tripods, for this type of structure the lateral soil bearing capacity is of particular importance for the bending moment transfer. The loadbearing behaviour of large-diameter monopiles, especially under cyclic continuous loading, is not yet fully understood and still the subject of research. A transition piece with access ladders, fenders and platforms is usually placed between the monopile

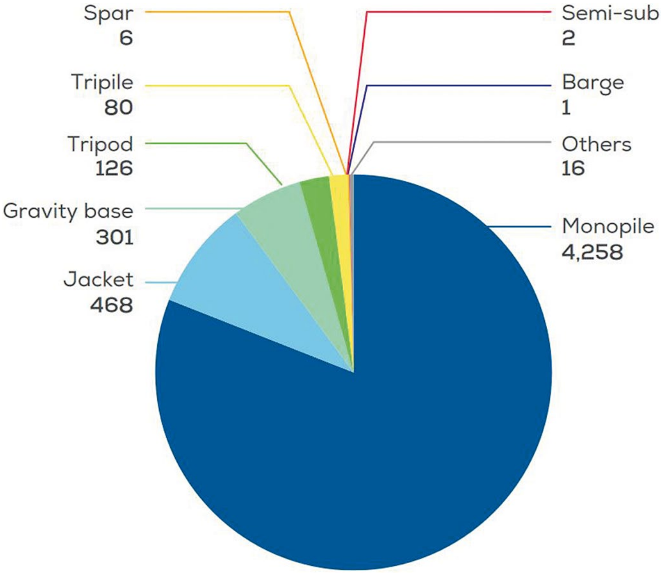


Fig. 2 Numbers of foundations connected to power grids in Europe by substructure type up to 2019 [4]

Fig. 3 Monopile at Steelwind, Nordenham

and the steel tower. This transition piece is connected to the monopile either via a grout connection (pipe-in-pipe plug connection with high-strength concrete in the joint) or via a bolted ring flange connection. Numerous cases of damage at the end of the first decade of this century led to intensive research work on the grouted connection [8]. The tubular steel tower installed above the grouted connection usually consists of several segments connected by ring flanges.

The gravity foundation (Fig. 1b) corresponds to the classic, solid flat foundation. Alternatively, steel or concrete boxes can be used, which are sunk and ballasted. Investigations into gravity foundations made of concrete for the first offshore parks in Denmark have shown that they become uneconomical with increasing water depth due to the technical effort and costs involved.

The tripod type (Fig. 1c) was built in the German test field Alpha Ventus and subsequently in two German wind farms in the North Sea. Three diagonal legs and horizontal braces support this foundation type. The connection to the ground is achieved with piles, which are placed in sleeves at the end of the tripod legs and connected by grouting. The German companies Weserwind (Bremerhaven) and Nordseewerke (Emden), which built this type, have unfortunately become insolvent. It turned out that this form of construction was extremely heavy and involved a tremendous amount of fabrication work with complicated, manually produced welds. This combination did not prove to be competitive.

In contrast, jacket constructions are much lighter (Fig. 1d, Fig. 4). The jacket is a truss-like structure of tubular members with a large footprint which, like the tripod foundation, is anchored to the ground with piles. It is very stiff, making it well suited to greater water depths and adverse ground conditions. In general, jacket structures are known from production platforms for the oil and gas industry. The individual members are made of circular tubes, which reduces the drag in the water, but makes the fabrication work at the nodes complicated. Therefore, research work is currently being carried out [9] following the concept of prefabricated nodes and standard tubes. This is a promising approach for series production.

The bucket foundation or suction caisson (Fig. 1e) is a steel foundation in the form of a large cylinder with a sealed top which is installed in the ground with the open end downwards by means of negative pressure. The entire soil mass enclosed by the foundation contributes to the stability of the foundation. It can be used in water as deep as 40 m. The advantages are the low cost of the simple structure and easy dismantling: When air is pumped in, the foundation rises out of the ground again. A further advantage over driven piles is the prevention of noise emissions during construction, which affect marine fauna. Although small obstacles can be removed by means of local soil liquefaction, a homogeneous subsoil structure is required to apply this concept. Buckets also represent an alternative to piles for jackets. Prototypes of this variant are still being tested.

Floating structures are available for water depths > 50 m. These include the tension leg concept shown in Fig. 1f. This concept consists of a floating body with a cylindrical shape which is submerged but not set down on the seabed. This floater is ballasted and several pontoons extend from it horizontally. The tendons are attached to these pontoons and anchored to the seabed. The tower is mounted in the middle of the platform. Other floating platform concepts are the spar, which is a pile-like buoy, and the semi-submersible, usually consisting of several columns and pontoons to create a large water plane, which also have reasonable draft and ballasting. The great advantage of floaters is that they can be easily moved to the offshore location. The research and development of floating concepts is currently being heavily promoted and advanced, as they enable the use of wind resources in deeper waters. To achieve the expansion tar-


(source: Institute for Steel Construction, LUH)

Fig. 4 Jacket in the Alpha Ventus wind farm


(source: Tennet [10], photo: Ulrich Wirrwa)

Fig. 5 BorWin Gamma transformer platform

gets, the industrial production of floating turbines and their installation in large numbers seems inevitable.

Offshore wind farms also include transformer platforms as shown in Fig. 5. These offshore platforms consist of the topside, the support structure and the foundation. For fixed platforms, jackets are usually constructed in combination with driven piles. The piles are driven through steel tubes (sleeves) attached to the side of the jacket legs. The so-called pile-sleeve connection is then grouted, i.d. the annular gap between driven pile and sleeve is filled with a high-strength mortar or concrete. The grout material contains very fine aggregates; it is cast underwater and hardens to form the connection.

The offshore platforms form the central element of a wind farm. They serve as collection points for the submarine cables from the individual wind turbines and are therefore also known as power sockets on the high seas. On the topside, transformers convert the internal voltage level to the voltage level of the high-voltage network. The high-voltage lines then transmit the green electricity from the offshore platform to a high-voltage direct current (HVDC) transmission station or directly to the mainland. The transformer platform shown in Fig. 5 has a total weight of 33 000 t, with the steel substructure (jacket including piles) weighing 10 000 t.

3 Verification of fatigue limit

The usual catalogue of structural stability analyses must be performed and checked for offshore wind turbines. Owing to the cyclic loads from wind, operation and waves and the extremely high number of more than one billion load cycles, verifying the fatigue strength is particularly important. Critical design details here are the connections, i.e. welds, bolted connections and the grouted connections already mentioned.

Since the beginning of offshore wind energy, monopiles have been a dominant construction solution. The monopiles are driven into the seabed, then a transition piece with a slightly larger diameter is placed on top and the joint is grouted. This allows any inclination to be compensated for. Until 2009, these cylindrical tube connections were mainly constructed with smooth steel surfaces and an overlap factor of approx. 1.5. This corresponded to the international state-of-the-art at that time, since a certain longitudinal shear loadbearing capacity had been experimentally proved even with smooth surfaces. Shear keys, which are welded to the outside of the monopile and the inside of the transition piece, were not used at all due to their unfavourable influence on the fatigue strength.

Peter Schaumann, author of this article, started scientific investigations of this connection type in 2003 with the aim of optimization. Approaches were, for example, a reduction in the overlap length or the use of alternative grout materials such as normal-weight concrete instead of high-strength concrete. It was determined that the existing international regulations at the time were not safe. This finding was first made known by the author in a presentation at the European Wind Energy Conference in 2008, which turned out to be too late. One year later, the first turbines in The Netherlands and the UK started slipping. A total of 600 turbines experienced slippage, causing property damage amounting to hundreds of millions of euros. Grout connections are now equipped with shear keys as standard (Fig. 6).

Lotsberg [7] conducted experiments with special box specimens using full-size grout thickness and shear key geometry to derive an analytical design approach that accounts for the compression struts that develop between shear keys by means of a vertical spring. The grout con-

(source: Institute for Steel Construction, LUH)

Fig. 6 Opened test body of a grout connection

nections of lattice structures are usually located underwater. However, the influence of the surrounding water on the fatigue behaviour was neglected in earlier tests and in the design methods. Further tests were conducted under submerged conditions [8]. The experimental investigations described involving small- and large-scale fatigue tests showed a significant decrease in endurable load cycles and identified a damage scenario that had not been observed before.

The damage to the grouted connections has led to concepts based on using bolted ring flange connections with high-strength prestressed bolts for monopiles instead of the grouted connections. This development was favoured by the fact that the monopiles can be driven vertically with such precision that subsequent correction is usually not necessary. Very large bolts are used for this connection technique, the largest of which currently available as high-strength prestressed bolts (HV bolts) are M72. However, it is now known that this connection also presents a number of technical challenges [11].

A research project to study these bolts was also carried out at the Institute for Steel Construction. The project compared the influence of various hot-dip galvanizing processes (normal temperature hot-dip galvanizing, high-temperature hot-dip galvanizing) with black bolts [12]. In this paper, probabilistic fatigue assessment, using the Monte Carlo Simulation technique, is utilized to compute the failure probability and investigate the influence of the scattering parameters on the fatigue performance of HV bolt sets in ring flange connections. Subsequently, an analytical fatigue calculation approach for large-size bolts, based on the local strain-life concept, is introduced. Results are compared from two different methods for determining the base material properties required. The underlying experimental investigations demonstrated the detrimental impact of hot-dip galvanizing on the fatigue performance of high-strength bolts. The decrease in the fatigue curve is about 20 % compared with black bolts. Nevertheless, the existing Eurocode 3 design curves could be confirmed. For very large bolts, however, further

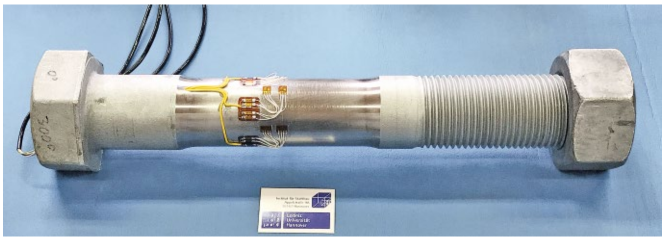

(source: Institute for Steel Construction, LUH)

Fig. 7 M72 measuring bolt

tests must be carried out. For this purpose, special measuring bolts are equipped with strain gauge measuring technology to quantify axial force and bending and torsion moments in the bolt (Fig. 7). Further, in situ monitoring data from offshore wind turbines equipped with an instrumented bolt in the monopile-to-transition piece bolted flange connection and strain gauges above that flange are used to derive empirical load transfer functions (LTF) [13]. The LTFs from the measured data are compared with the tri-linear function according to Schmidt/Neuper and a finite element model considering the monopile-flange inclination, which shows good agreement. As an alternative to ring flange connections, Veljkovic et al. [14] suggested the construction of friction connections for large steel towers. This connection type would avoid ring flange-to-shell welds and tensile forces in the bolts, both of which exhibit poor fatigue resistance.

In addition, the fatigue strength of the welds to extremely thick plates, as shown in Fig. 8, poses a particular challenge. Recent research investigated the behaviour under fatigue loading and tested new welding methods and post-weld treatment processes for the butt welds of monopiles [15]. Owing to the further development of laser-based and optical scanning methods, the field of reverse engineering is increasingly gaining attention in numerical fatigue assessment, which also includes a further enhancement of the fatigue analysis approaches [17]. The digitized 3D weld geometry surfaces are prepared for FE simulations of the real notch factor K_t to estimate the fatigue-critical weld transition numerically in terms of the maximum K_t value, see Fig. 9. Combining the test results with the statistical evaluation of the notch factors revealed a definite correlation between fatigue life and geometrical notch effect. Besides geometric effects, stresses and mechanical and fracture properties play a large role in fatigue behaviour. The latter were investigated by Mehmanparast et. al [16] with interlaboratory tests.

To increase the competitiveness of jacket substructures compared with monopiles, it is necessary to switch from individual to serial jacket production based on automatically fabricated tubular joints combined with standardized pipes. Besides the improvements for a serial manufacturing process, the automatically welded tubular joints show great potential in terms of fatigue resistance, for example, due to a smooth and highly reproducible weld geometry. However, owing to the lack of suitable S-N curves, these benefits are not considered yet within the fatigue design process of automatically fabricated jacket

(source: Institute for Steel Construction, LUH)

Fig. 8 Test body of a fatigue-stressed weld with cracking clearly visible

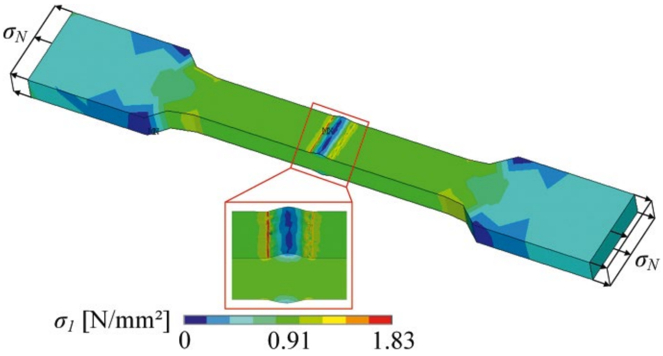


Fig. 9 Reverse engineering application on butt-welded joint

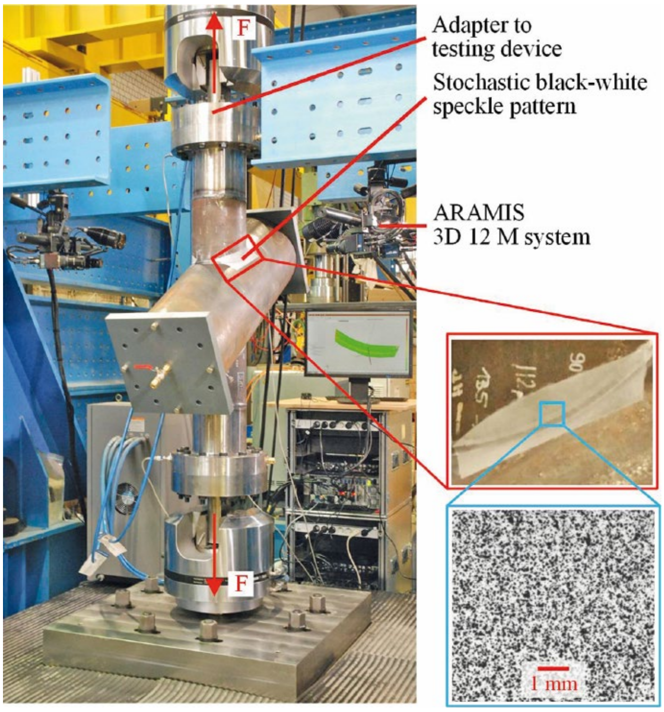


Fig. 10 Test setup for axial fatigue tests on automatically welded tubular X-joints including two ARAMIS digital image correlation systems

substructures according to current standards. Therefore, axial fatigue tests on automatically welded tubular X-joints have been performed as shown in Fig. 10. Based on these tests, a fatigue strength increase of about 10 % (FAT 126) compared with the currently valid S-N curve (FAT 114) was obtained with a comparatively low standard deviation of $s_N = 0.147$ [18]. Similar results of fatigue tests on robot-welded tubular joints were published in [19] and [20].

As a synergy effect, an application of the digital image correlation (DIC) technique to cyclically loaded welded joints was developed to identify and analyse the transition from crack initiation to crack propagation [21]. By doing so, initial macroscopic cracks with lengths of about 1–1.5 mm could be detected [22], [23]. Owing to the chronological storage of the 3D digital images during the fatigue test, the DIC method used also includes the option of reviewing the history of the fatigue test and the 3D surface of the specimen to analyse, for example, the occurrence of outliers due to undercuts or sharp notches afterwards. As an example, Fig. 11 shows the typical evolution of the fatigue-induced damage within the hot spot of the tubular X-joints tested. In Fig. 11b several damage-induced strain hot spots can be seen within the cord-sided notch. These relatively widely distributed hot spots increased and merged during the ongoing fatigue test to create the larger damaged area as shown in Fig. 11c. Finally, a first crack could be visually detected in the ARAMIS images as shown in Fig. 11d.

To test the specimens in the aforementioned projects and many other important research projects, the Support Structures Test Centre of Leibniz University Hannover (TTH) (Fig. 12) was opened in 2014 in the immediate vicinity of the wave channel for investigations in coastal engineering.

The wave channel is used for the testing support structures under hydrodynamic loading and will be further expanded in the next few years. It will then not only be possible to study the effect of waves on structures, but also the simultaneous effect of currents in a deep section. The wave channel is currently 320 m long × 5 m wide × 7 m deep. The deep part of the channel will later have a depth of between 15 and 20 m. This test facility will be unique worldwide.

In the test centre, support structures (towers and foundations) can be investigated experimentally at a scale of 1:10 to 1:3. For this purpose, a foundation test pit 10 m deep and a span with abutment walls standing over corners are available. In addition, the test centre houses special laboratories for steel, concrete, fibre-reinforced composites and geotechnical investigations.

Clearly defined test conditions up to extreme loads guarantee reproducible results that provide answers to complex questions. By combining structural models, numerical calculations and large-scale experiments, onshore and offshore wind turbines can be further developed and simulation models validated with regard to higher turbine availability and cost efficiency. The fatigue behaviour of the structures under the continuous actions of waves, wind and system operation can be investigated in fast motion. Optimization approaches and system reserves can

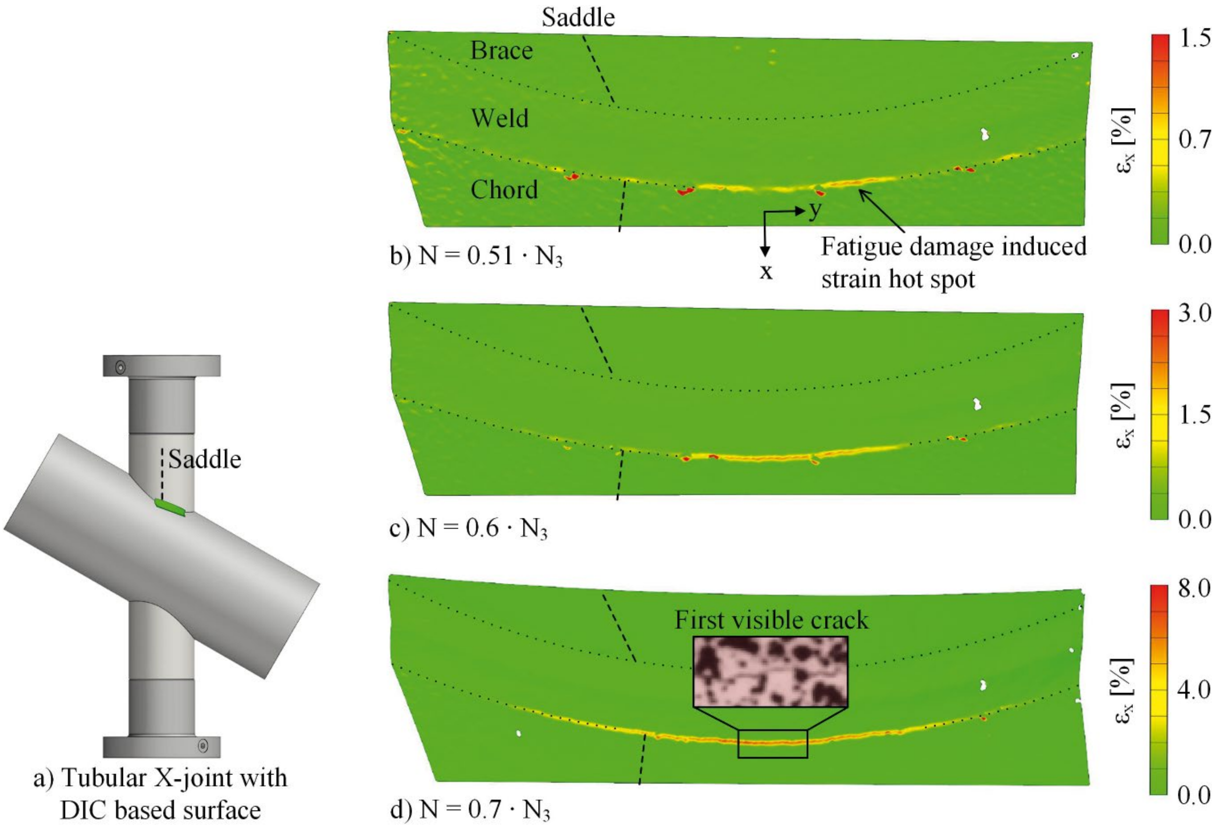


Fig. 11 Measured fatigue damage evolution within the hot spot of a robot-welded tubular X-joint (durability N_3 corresponds to through-thickness cracking)

thus be identified and developed in a time-saving manner. Environmentally compatible construction techniques can also be systematically examined in the test centre.

Fig. 12 shows the 10 m deep foundation pit filled with sand. The sand is installed according to a special technique to examine the behaviour of the soil in detail, for example, during pile penetration. The facility can also be flooded to simulate real conditions as in the North and Baltic Seas. In the rear part there is a strong 3D wall/floor ensemble with not only a horizontal part, but also two walls at right-angles. Loads can be applied three-dimensionally here.

4 DIN 18088 – the new series of standards covering support structures for wind energy turbines and platforms

Since November 2014, experts at the German Institute for Standardization (DIN) have been developing the standard texts for DIN 18088 "Supporting structures for wind turbines and platforms" [3]. In future, this will be the standard applicable in the approval procedure for onshore and offshore wind turbines. This series of standards includes regulations on the effects on support structures for onshore and offshore wind turbines and platforms, the safety concept and design rules for support structures using prestressed concrete and steel, and for foundations. Parts of the standards which are still to be developed deal with grout connections and monitoring and maintenance.


(source: Faculty of Civil Engineering & Geodetic Science, LUH)

Fig. 12 View of the Support Structures Test Centre at Leibniz University Hannover

Part 3 is the part of DIN 18088 that is crucial for verifying the loadbearing resistance in terms of ultimate and fatigue loads on the steel support structures for wind turbines and platforms. This part regulates the assessment methods for structural design and describes some special verifications that are not addressed in the Eurocodes. Those include, for example, regulations for the prestressed bolted connections of the ring flanges. A section of particular importance is that on the selection of materials for fracture toughness and through-thickness properties. Based on statistical data from meteorological measurements and stress spectra of wind turbines, the dimensioning tables of Eurocode 3, Parts 1–10, were adapted to the conditions for offshore wind turbines in the German North and Baltic Seas.

Although inclusion in the BSH (Federal Maritime and Hydrographic Agency) standard [24] is still pending, these new standards will have an impact on future wind energy projects.

5 Final remarks and further challenges

Offshore wind turbines are essential as part of the transition to cleaner energy. The operating results of the first wind farms prove the excellent conditions under which they can use the wind supply out in the North and Baltic Seas. Unlike these locations, where structures fixed to the seabed can be used, floating structures are being developed for the Mediterranean Sea and Atlantic Ocean. In addition, as turbines are located far off the coast, they have the great advantage that acceptance among the population is much higher than is the case with onshore wind farms.

Owing to the water depths, soil conditions and size of the turbines (up to 14 MW offshore), support structures are becoming larger and larger; monopiles these days reach diameters of 10 m. At the same time, however, the accuracy requirements for the ring flange connections are increasing, since the greater rigidity of this type of construction requires preparation and shape accuracy of the parts that is even more precise. This pushes the technical feasibility of these structures to their limits.

Furthermore, fatigue analysis still raises challenges that need to be addressed. These include the analysis of the three common connection types: welds, ring flanges and grouted connections. Regarding the welds, the thickness reduction must be checked for the fatigue resistance of steel plates about 100 mm thick. In addition, when calculating the fatigue resistance of automatically welded joints, the high quality of the welded seams needs to be considered. Analysis methods based on local concepts for fatigue verification need further development and the actual geometry of the welds has to be distinguished more precisely. Furthermore, the impact of ring flange tolerances on the fatigue behaviour of the bolts has to be quantified. Considering the grouted connections, the impact of submerged conditions on the fatigue performance has to be evaluated. The research at the Institute for Steel Construction focuses on tackling these issues.

Further, there are special normative regulations for the design of offshore wind turbines. Wherever possible, reference is made to the Eurocodes. However, many issues are not addressed in the Eurocodes. Therefore, the approvals must be based on additional regulations.

In Germany, the political boundary conditions are just changing. The intended capacity for offshore wind energy has recently been increased to 20 GW in 2030 and 40 GW in 2040. This gives hope to the industry after a period of regression. It will require great efforts to achieve these goals. For climate protection, it will be worthwhile in any case.

Acknowledgements

This article is an extended and modified English version of [25].

The results presented were developed in different joint research projects, two of them managed by FOSTA (‘FAT-InWeld’, 19104 N, and ‘Big Bolts’, 486 ZN) via AiF within the programme for promoting the Industrial Collective Research (IGF) of the German Ministry of Economic Affairs and Energy (BMWi) and one managed by PtJ (‘GROWup’, FKZ 0325290) and funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). The authors express their deep gratitude for the financial support received from the BMWi, AiF, FOSTA and the companies involved in the projects.

Open access funding enabled and organized by Projekt DEAL.

References

[1] European Commission (2018) *A Clean Planet for all – A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0773

[2] WindEUROPE (2019) *Our energy, our future – How offshore wind will help Europe go carbon-neutral*. https://windeurope.org/about-wind/reports/our-energy-our-future/

[3] DIN-18088-3 (2019) Support structures for wind energy converters and platforms, Parts 1–5, Berlin: Beuth Verlag.

[4] WindEUROPE (2020) *Offshore Wind in Europe – Key trends and statistics 2019*. https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2019.pdf

[5] Schaumann, P.; Kleineidam, P.; Wilke, F. (2004) *Fatigue Design bei Offshore-Windenergieanlagen* in: Stahlbau 73, No. 9, pp. 716–726. https://doi.org/10.1002/stab.200490175

[6] EEW Holding GmbH & Co. KG (2021) *Monopiles/XL Monopiles/Transition pieces*. https://eew-group.com/portfolio/structural-pipes/monopiles/

[7] Lotsberg, I. (2013) *Structural mechanics for design of grouted connections in monopile wind turbine structures* in: Marine Structures 32, pp.113–135.

[8] Schaumann, P.; Raba, A.; Bechtel, A. (2017) *Fatigue behaviour of grouted connections at different ambient conditions and loading scenarios* in: Stahlbau 85, No. 12, pp. 822–827, https://doi.org/10.1002/stab.201610434

[9] Schaumann, P.; Schürmann, K.; Pittner, A.; Rethmeier, M. (2018) *Prediction of the initial fatigue crack location of automatically welded tubular joints for jacket support structures* in: Proc. of 7th Intl. Conf. on Structural Engineering, Mechanics & Computation (SEMC), 2–4 Sept 2019, Cape Town, South Africa, https://doi.org/10.1201/9780429426506

[10] Tennet (2019) *Float-over läuft!* https://www.tennet.eu/de/unser-netz/offshore-projekte-deutschland/borwin3/blog-borwin3/article/2018/10/11/float-over-laeuft/ (accessed 4 Dec 2019).

[11] Lüddecke, F.; Victor, A.; Schwedler, M. (2019) *Analyse des Einflusses fertigungsbedingter Imperfektionen auf die Schraubenkraft an großen Ringflanschverbindungen/ Welche Auswirkungen ergeben sich auf die Nachweise für die Ermüdung von Schraubengarnituren bis zur Größe M72?* in: Der Prüfingenieur 55, pp. 42ff.

[12] Schaumann, P.; Eichstädt, R.; Stang, A. (2018) *Advanced performance assessment methods for high-strength bolts in ringflange connections* in: Stahlbau 87, No. 5, pp. 446–455, https://doi.org/10.1002/stab.201810601

[13] Weijtjens, W.; Stang, A.; Devrient, C.; Schaumann, P. (2021) *Bolted ring flanges in offshore wind support structures – in-situ validation of load transfer behaviour* in: Journal of Construction Steel Research 176, https://doi.org/10.1016/j.jcsr.2020.106361

[14] Veljkovic, M.; Feldmann, M.; Naumes, J.; Pak, D.; Rebelo, C.; da Silva, L. S. *(2010) Friction connection in tubular towers for a wind turbine* in: Stahlbau 79, No. 9, pp. 660–668

[15] Collmann, M.; Schaumann, P. (2018) *Transverse butt welds as fatigue critical detail of steel towers and monopiles – Influence of the geometrical notch effect on the fatigue resistance* in: Stahlbau 87, No. 9, pp. 888–896, https://doi.org/10.1002/stab.201810016

[16] Mehmanparast A,Taylor J, Brennan F, Tavares I. (2018) *Experimental investigation of mechanical and fracture properties of offshore wind monopile weldments: SLIC interlaboratory test* result in: Fatigue Fract Eng Mater Struct. 41, pp. 2485–2501, https://doi.org/10.1111/ffe.12850

[17] Schaumann, P.; Schürmann, K. (2019) *New proposal to express notch stress approach results by equivalent SCFs* in: International Journal of Fatigue 119, pp. 1–119, https://doi.org/10.1016/j.ijfatigue.2018.09.009

[18] Schürmann, K.; Schaumann, P.; Pittner, A.; Rethmeier, M. (2020) *Experimental investigations on the fatigue resistance of automatically welded tubular X-joints for jacket support structures* in: Journal of Physics: Conference Series 1669, https://doi.org/10.1088/1742-6596/1669/1/012022

[19] Papatheocharis, T.; Sarvanis, G. C.; Perdikaris, P. C.; Karamanos, S. A.; Zervaki, A. D. (2020) *Fatigue resistance of welded steel tubular X-joints* in: Marine Structures 74, https://doi.org/10.1016/j.marstruc.2020.102809

[20] van Wittenberghe, J.; Thibaux, P.; van Poucke, M. (2019) *Large Scale Resonant Fatigue Testing of Welded Tubular X-joints for Offshore Jacket Foundations* in: Proc. of ASME 2019 38th Intl. Conf. on Ocean, Offshore & Arctic Engineering (OMAE), 9–14 Jun 2019, Glasgow, UK.

[21] Schaumann, P.; Schürmann, K.; Pittner, A.; Rethmeier, M. (2019) *Automatically Welded Tubular X-Joints – Welding Procedure and Prediction of the Technical Fatigue Crack Location* in: Proc. of 29th Intl. Ocean & Polar Engineering Conference, 16–21 Jun 2019, Honolulu, USA, pp. 4098–4105.

[22] Schürmann, K. (2021) *Fatigue Behavior of Automatically Welded Tubular Joints for Offshore Wind Energy Substructures*. Dissertation. Institute for Steel Construction, Leibniz University Hannover (in preparation).

[23] Friedrich, N.; Ehlers, S. (2019) *Crack Monitoring in Resonance Fatigue Testing of Welded Specimens Using Digital Image Correlation* in: Journal of Visualized Experiments (151), https://doi.org/10.3791/60390.

[24] BSH (2015) *Standard Konstruktion: Mindestanforderungen an die konstruktive Ausführung von Offshore-Bauwerken in der ausschließlichen Wirtschaftszone (AWZ)*, https://www.bsh.de

[25] Schaumann, P.; Böhm, M. (2020) *Die geplante Energiewende in Deutschland wird nur mit einem weiteren Ausbau von Offshore Windparks gelingen / Die Ermüdungsfestigkeit der hochbelasteten stählernen Tragstrukturen bedarf dabei spezieller Aufmerksamkeit* in: Der Prüfingenieur 56, pp. 36ff.

Authors
Prof. Dr.-Ing. Peter Schaumann
schaumann@stahl.uni-hannover.de
Leibniz University Hannover
Institute for Steel Construction
Appelstr. 9A
30167 Hannover, Germany

Manuela Böhm (corresponding author)
boehm@stahl.uni-hannover.de
Leibniz University Hannover
Institute for Steel Construction
Appelstr. 9A
30167 Hannover, Germany

Karsten Schürmann
karsten.schuermann@ramboll.com
Ramboll Deutschland GmbH
Offshore Wind Structures
Andreaestraße 3
30159 Hannover, Germany

How to Cite this Paper

Schaumann, P.; Böhm, M.; Schürmann, K. (2021) *Improvements in the fatigue design of support structures for offshore wind turbines.* Steel Construction 14, No. 2, pp. 74–82.
https://doi.org/10.1002/stco.202000060

This paper has been peer reviewed. Submitted: 30. November 2020; accepted: 16. February 2021.