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A REVIEW ON EXPERIMENTAL FATIGUE ANALYSIS OF TUBULAR JOINTS FOR OFFSHORE WIND TURBINE SUBSTRUCTURES

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Abstract. *The scientific community is devoting more attention to the wide scope of offshore wind turbine structures. Since such structures are subjected to high level of fatigue loads as well as a large number of load cycles caused by wind, waves and turbine operation, the fatigue performance of welded connections is usually a design driving criteria. In this paper, a brief review on experimental fatigue analysis of circular hollow section joints for jacket structures is presented. Special emphasis is given to full-scale experimental testing. In order to face some of the challenges in this area of expertise, an experimental research plan within the framework of the Innovative Training Network (ITN) AEOLUS4FUTURE is introduced, aiming to understand and validate the fatigue performance of circular hollow section joints produced by an automated process, using Tandem MIG/MAG welding.*

1 INTRODUCTION

In the last two decades wind turbines moved offshore due to the limited in-land space for the development of onshore wind farms, the possibility to accommodate even more wind power under significant steadier wind conditions, and the lower environmental impact inherent to an Offshore Wind Turbine (OWT) [1]. However, the support structure of an OWT has a great contribution to the cost-effectiveness of the overall system, especially in deep waters. As current practice, monopiles are the preferred type of support structures for water depths up to 30 m [2]. Thus, monopile diameters up to 10 m are subject of latest design concepts, leading to manufacturing, transportation and erection challenges. However, more attention have been payed to the use of jacket structures to larger water depths. The design of jacket substructures for offshore wind turbines is still in an early stage of development although the use of such substructures has the potential to become the dominant solution due to the expected optimization of design methods, fabrication techniques (in particular with respect to the joints), transportation and erection operations [3, 4].

Since OWTs are subjected to high level of fatigue loads as well as a large number of load cycles caused by wind, waves and turbine operation, the fatigue performance of welded Circular Hollow Section (CHS) joints is usually a design driving criteria. The fatigue behaviour of welded CHS joints is a well-recognised research problem in the design of tubular structures [5].

The fatigue strength of such joints depends on the absolute and relative size of its members (size effect), on the load case, on the initial crack-like imperfections, and on the welding residual stress fields [6]. Research addressing these fatigue issues has been carried out during the last 35 years, mainly by the offshore industry [5, 6].

The main contribution of this paper is to analyse the contents of existing publications in fatigue analysis of welded CHS joints of jacket structures, and provide an approach for future courses of action in experimental fatigue testing. Special emphasis is given to most recent full-scale experimental testing on scope of OWTs. In order to face some of the challenges in this area of expertise, an experimental research plan within the framework of the Innovative Training Network (ITN) AEOLUS4FUTURE is introduced, aiming to understand and validate the fatigue performance of welded CHS joints produced by an automated process, using Tandem MIG/MAG welding.

2 FATIGUE DESIGN OF OWT SUPPORT STRUCTURES

OWTs are subjected to high level of fatigue loads as well as a large number of load cycles caused by wind, waves and turbine operation. For instance, the number of load cycles generated from the rotor of an OWT within its design life time (usually 20 years) may reach more than 1x 10^9 load cycles [7]. Furthermore, geometric discontinuities lead to stress concentrations that must be considered within the fatigue assessment [8].

Welded CHS joint design is a well-known field of research of the offshore industry. For fatigue verifications, it is common practice to evaluate the calculated damage based on Hot Spot Stresses (HSSs) in combination with related S-N curves [9]. A typical sequence in fatigue design of welded CHS joints of support structures for offshore wind turbines is shown in Table 1.

Different concepts of S-N curves are developed and referred to in the literature. It is thus important that the stresses are calculated in agreement with the definition of the stresses to be used together with a particular S-N curve [7]. Three different concepts of S-N curves are defined: i) nominal stress S-N curve; ii) hot spot stress S-N curve for plated structures and for welded CHS joints; and iii) notch stress S-N curve, used only in special cases where it is difficult to assess the fatigue life using other methods. Schematization of the different stress approaches is given in Figure 2, for an exemplificative geometry discontinuity, where a fatigue crack is expect to grow

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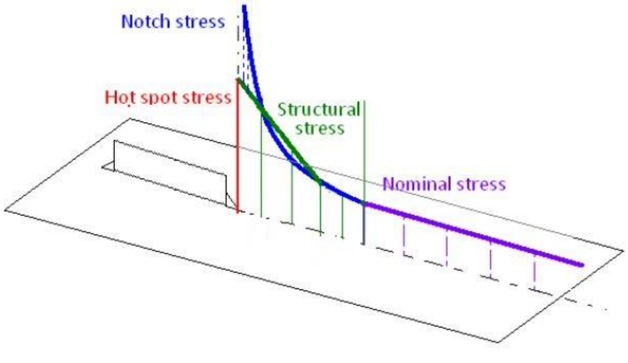


Figure 1. Nominal stress vs structural stress; hot spot stress vs notch stress [12].

Typical fatigue assessment procedure	Description
1. Definition of fatigue loading	Based on wind loading, control system influence and wave load
2. Identification of locations to be assessed	Structural discontinuities, joints, anode attachment welds, repairs, and so on
3. Global OWT fatigue analysis	Calculation of the short-term nominal stress range distribution at each identified location
4. Local joint stress analysis	Determination of the hot-spot SCF from parametric equations or detailed finite element analysis
5. Identification of fatigue strength data	S-N curve is dependent on environment, construction detail and fabrication among others
6. Identification of thickness correction factor	Application of thickness correction factor to compute resulting fatigue stresses
7. Fatigue analyses	Calculation of the accumulated fatigue damage from weighted short-term fatigue damage
8. Further actions in order to improve fatigue life	Improve fatigue capacity using: - more refined stress analysis - fracture mechanics analysis - change detail geometry - weld profiling or grinding - improved inspection and monitoring

Table 1. Typical fatigue assessment procedure (adapted from [13]).

3 EXPERIMENTAL FATIGUE ANALYSIS OF WELDED CHS JOINTS FOR OWT SUBSTRUCTURES

As summarized in section 2, it is common practice to evaluate fatigue damage based on HSSs in combination with related S-N curves. The existing S–N curves for tubular connections estimate the fatigue life of welded CHS joints, which were developed through experimental research over the last decades [14-17]. However, the offshore industry demands the development of practical and reliable strategies to enhance the fatigue performance of welded CHS joints.

Over the years, significant research efforts have been devoted to post-welding treatments, i.e., toe grinding, tungsten inert gas dressing and weld profiling, demonstrating the respective enhancement on the fatigue strength of welded CHS joints [18–24]. Furthermore, the use of new materials and high strength steels have been tested for offshore applications, being important to carry out fatigue tests on welded CHS joints [24-26]. Nevertheless, there is a need to investigate design uncertainties on the scope of fatigue behaviour of welded CHS joints, e.g., complex joint geometries, thickness effect, the welding operation and residual tension stresses [6, 27-33].

In this section, the contents of most recent publications in fatigue analysis of welded CHS joints for jacket structures is analysed, in order to provide an approach for future courses of action in experimental fatigue testing. Special emphasis is given to most recent full-scale experimental fatigue testing.

3.1 Schumacher and Nussbaumer [6] - 2005

This article refers to fatigue tests carried out on a total of 8 welded CHS large scale K-joints. Measured hot-spot stresses in the joints were compared with hot-spot stresses calculated using the current design guidelines.

It was found that the measured values are considerably lower than the calculated values. The fatigue tests has clearly demonstrated the effect of size on the fatigue strength of welded CHS joints. The size correction factor integrated into the S-N design curves of the specifications, does not seem to represent this significant effect justly. Further research on targeted S-N curves and a representative size effect is recommended.

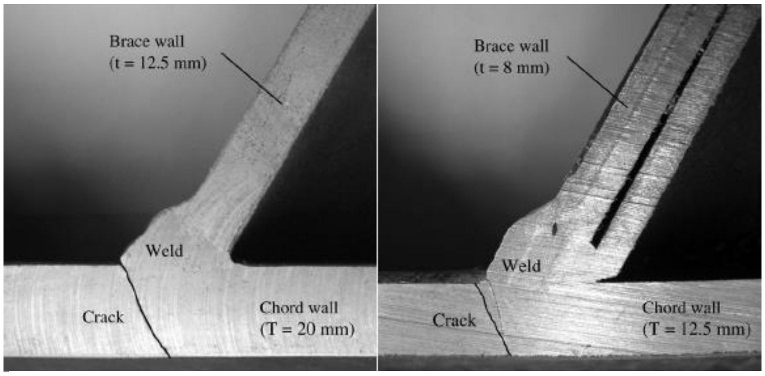


Figure 2. Cracks through chord thickness [6].

3.2 Shao Y. B. [27] – 2007

This paper presents general remarks of the effect of the geometrical parameters on the stress distribution in the hot spot stress region for welded CHS T- and K-joints subjected to brace axial loading. They are chord thickness parameter γ (a ratio of radius/thickness of the chord), brace diameter parameter β (a ratio of brace diameter/chord diameter) and brace thickness parameter τ (a ratio of brace thickness/chord thickness).

It has been found that parameter γ has the same effect on the stress distribution for T- and K joints. Remarkably it influences the stress distribution and the location of the peak stress along the weld toe. Parameter β, however, has different effects on T- and K-joints. It influences the stress distribution of T-joints but has no effect on the stress distribution of K-joints. For parameter τ, it has no effect on the stress distribution for both welded CHS T- and K-joints.

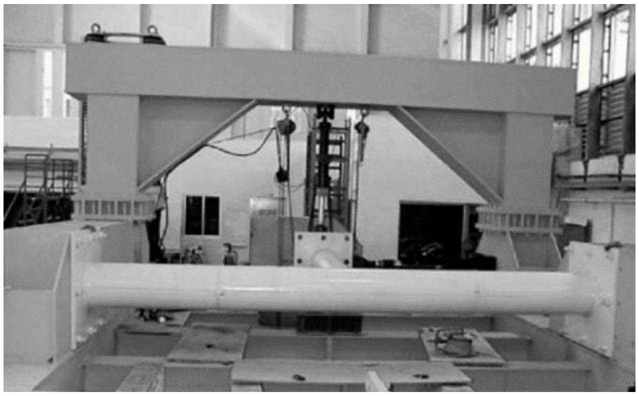


Figure 3.View of test rig for T-joint specimens [27].

3.2 Mangerig and Romen [28] - 2009

This paper refers to fatigue tests carried out on a total of 7 welded CHS joints. Comparative tests comprising specimens with a post-weld treatment method (partially UIT-treated welding) were performed. Furthermore a repair technique was investigated; for this purpose the entire fatigue crack of an already damaged specimen was grinded and rewelded.

The comparison of two specimens, which were identical except for the brace wall thickness indicate the clear existence of the so called size effect. Considering the results of a specimen treated partially by the UIT procedure, a significant enhancement of the fatigue life can be stated for this post-weld treatment. For this test, 1.4×10^6 more load cycles, compared to the untreated specimens, could be achieved till first fatigue failures occurred in form of initial cracks at the non-treated welding toe of the intersection between brace and welding seam. After the fatigue test of a previously tested specimen it was repaired by completely grinding off the entire fatigue crack rewelding. The test showed that the repair technique used, combined with the post-weld treatment UIT, extends the fatigue life at least by about the same value of load cycles that was achieved for the original unrepaired specimen.

Figure 4. X-joint [28].

3.3 Jo et al. [29] - 2011

In this research, large-scale fatigue tests of welded K-joints under the balanced in-plane bending were carried out to investigate the fatigue behaviour of a specific steel (API 2W Gr.50.). Figure 5 shows the test set, loading frames, and an actuator system. After connecting both of the top portions of the brace by a stiff girder, a 980 kN dynamic actuator was placed on the top of the specimen. Both ends of the specimen were clamped by bolts to allow the movement in the chord direction. To prevent any disconnection during the test, both ends of the test specimen were fixed by a hydraulic bolting device. The test results based on the hot spot stress were in agreement with the design curves.

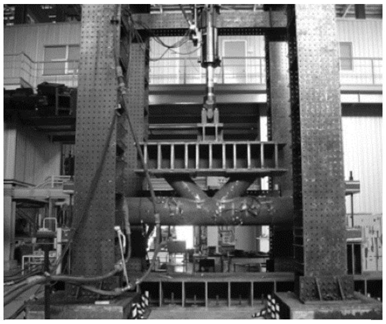


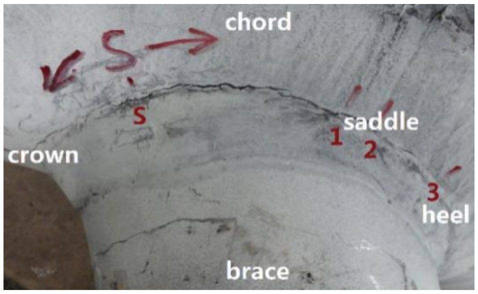
Figure 5. View of K-joint [29].

3.4 Yue et al. [30] - 2012

In Yue et al. [30] it is attempted predict the fatigue life of a multi-planer welded CHS KK joints based on scalded model tests. Although KK joints among jacket structures suffer complicated combined loading, the axial load is usually predominant. Therefore, the fatigue performance of the KK joint was evaluated under axial loading. From the comparison and analysis of their HSS, the fatigue life of the real structure was provided based on the scalded model.

Cycle	Observed Results	Crack stage
77.0×10^4	Crack initiated at Point *S*.	Initiation
103.3×10^4	Crack propagated along the weld toe toward both sides.	Stable propagation
112.7×10^4	Crack propagated to Point 1; Cracks initiated around Point *S*.	Unstable propagation
112.9×10^4	Crack propagated to Point 2; Cracks initiated around Point *S*.	
113.9×10^4	Crack propagated to Point 3; Crack in Point *S* penetrated chord.	Fatigue failure

(a)



(b)

Figure 6. (a) Comprehension of the crack initiation and propagation. (b) Crack Visualization [30].

3.5 Qian et al. [31] - 2013

In this research, it is intended to examine the fatigue behaviour of two large-scale X-joints welded using the enhanced partial joint penetration welds tested under constant-amplitude brace in-plane bending actions, as shown in figure 7, covering the initiation and propagation of weld toe cracks and the effect of weld grinding. Post-weld grinding.

The experimental fatigue research confirmed the satisfactory fatigue performance of the welded X-joints welded using enhanced partial joint penetration welds in comparison with the S-N curves developed for welded CHS joints with complete joint penetration welds. Significant enhancement on the fatigue life provided by the weld surface grinding and toe grinding as was verified.

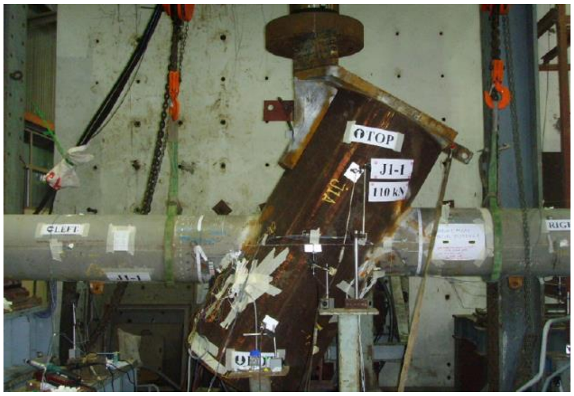


Figure 7. View of X-joint [31].

3.6 Kuhlmann et al. [32] - 2014

This paper refers to the results of the FOSTA P815 research project, dealing with the fatigue behaviour of welded K- and KK-joints with thick walled chords.

For the determination of the fatigue strength of thick-walled welded CHS joints, an extensive test program was carried through small scale fatigue tests under brace loading, chord loading and combined loading. Furthermore a large-scale test was performed.

The outcomes of this research project were summarized as recommendations on planning, fabrication and design for practitioners. Particular focus was devoted the size effect in the component fatigue tests. Recommendation regarding the influence of post-weld treatment on the fatigue resistance using the high-frequent hammering technology was provided.

Figure 6. View of K-joint [32].

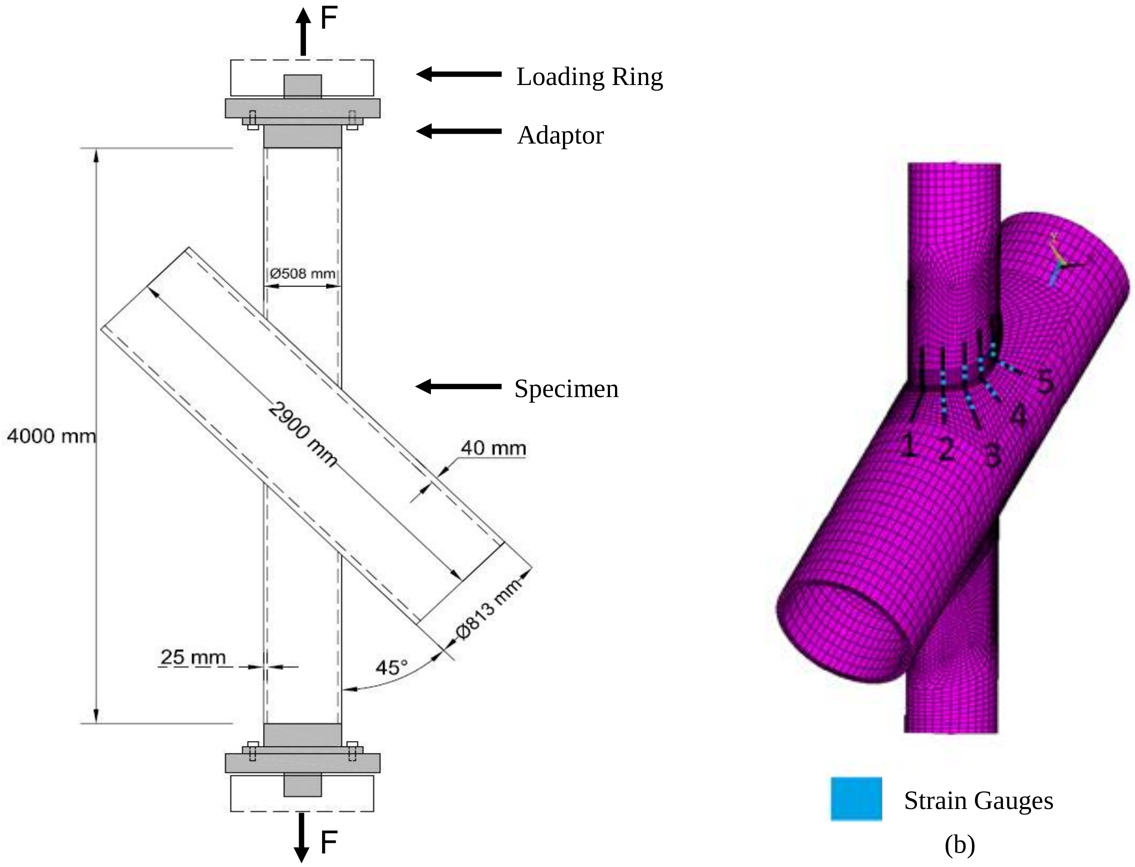
4 WAY FORWARD

In the previous section, the contents of most recent publications in fatigue analysis of welded CHS joints for jacket structures was analysed.

As suggested by several publication, the size effect has to be taken into account in the fatigue testing of welded CHS joints [6, 27, 28, and 32]. In fact, the size effect for proportionally scaled joints appears to be greater than the size correction included in design lines [6]. Previous research work was mostly focused on the study of the value of the peak stress, however, the stress distribution along the weld toe is very critical for the prediction of the fatigue life of welded CHS joints [27]. Therefore, further researches intended to investigate the fatigue behaviour of thick walled welded CHS joints, as used in the offshore industry, should be performed through large scale fatigue testing.

The post-weld treatment methods can contribute to enhancement in the fatigue life of welded CHS joints, as demonstrated by previous researches [28, 31 and 32]. The favourable effect achieved by this post-weld treatment could also be recognized for structures that were already loaded by high-cycle fatigue [28].

In order to push superior risk and cost considerations to a new level, a research project within the framework of the Innovative Training Network (ITN) AEOLUS4FUTURE is under development, in the scope of fatigue behaviour of support structures for OWTs. If successful, the proposed research project can provide a valid understanding of the fatigue behaviour of automated tandem MIG/MAG welds. Automated welding technologies have already been development, for the production of CHS joints [33]. The production automation allows the delivery of standardized components and the application of dual wired welding processes (Tandem MIG/MAG), which can only be applied by mechanised or robotic welding due to the required precision in positioning. Therefore, there is a need to investigate the fatigue behaviour of the assembled joints, as such technology allows welding from both sides of the steel tubes (as strategy to improve fatigue behaviour), higher weld deposition rates, lower welding time and overall cost reduction.



(b)

(a)

Figure 7. (a) X-Joint finite element model; (b) Load simulation and hotspot stress location.

Regarding the experimental investigation, the fatigue behaviour large scale welded X-joints, overcoming the referred size effect [6, 27, 28, and 32]. As welded CHS joints suffer complicated combined loading, the fatigue tests shall be performed under individual loading scenarios: axial load, in-plane bending and out-of-plane bending. The preliminary test setup is represented in Figure 7. An X-joint configuration is adopted as HSSs are more easily located [28]. These stresses are then located and monitored throughout the time of fatigue testing, as this are the expected locations for crack initiation. Results of the experimental campaign will be used to validate numerical models. Furthermore, a numerical investigation will be performed by use of local concepts to achieve a deeper understanding of the damage mechanism. Finally, parametrical studies and differences on fatigue life will be quantified between the standard and the advanced methods. Parameters such as loading and diameter/thickness ratio will be investigated.

CONCLUSIONS

The offshore industry demands the development of practical and reliable strategies to enhance the fatigue performance of welded CHS joints. In this paper, the contents of most recent publications in fatigue analysis of welded CHS joints were analysed, in order to provide an approach for future courses of action in experimental fatigue testing.

As suggested by several publication, the size effect has to be taken into account in the fatigue testing of circular hollow section joints [6, 27, 28, and 32]. The post-weld treatment methods can contribute to enhancement in the fatigue life of welded CHS joints, as demonstrated by previous researches [28, 31 and 32]. The favourable effect achieved by this post-weld treatment could also be recognized for structures that were already loaded by high-cycle fatigue [28].

In order to face some of the challenges in this area of expertise, an experimental research plan within the framework of the Innovative Training Network (ITN) AEOLUS4FUTURE was introduced. If successful, the proposed research project can provide a valid understanding of the fatigue behaviour of automated tandem MIG/MAG welds, overcoming size effect.

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