Remaining fatigue lifetime of welded tubular joints of offshore structures using detailed stress analysis based on 3D scans

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Abstract

Corrosion and fatigue damage are the primary factors contributing to the degradation of offshore steel substructures. In the FlexWind project, funded by the Energy Transition Fund of the Belgian federal government, an innovative approach will be developed to assess the remaining fatigue resistance of offshore wind turbine foundations. Instead of relying solely on design documentation, the as-built conditions will be considered. More specifically, the aim is to enhance the analysis of local aspects, such as surface degradation and the actual weld geometry, beyond current standard practices. To this end, a framework for semi-automated reconstruction of finite element models based on 3D scanned data is developed. The required local geometrical data is obtained using a handheld 3D laser scanner. As only the outer surfaces are accessible to the scanner, the framework needs to reconstruct the inaccessible parts. The finite element model is used to determine the fatigue governing local stresses that serve as the input for fatigue life prediction of the welded joints.

Keywords: Fatigue, Life extension, 3D laser scanning, Offshore wind

1 Introduction

Offshore wind turbines and their foundations are typically designed to have an operational lifetime of 20 years [1]. From 2029 onwards, many wind turbines in the North Sea will reach their design lives, as shown in Figure 1. Once the design life is reached, there are three possible scenarios for the substructures of these turbines; decommissioning, lifetime extension or repowering. The latter two are economically and ecologically more beneficial, but require an extensive investigation to ensure the continued safe operation of the substructure. The goal of the FlexWind project is to develop a framework to determine the remaining lifetime of fixed-bottom substructures. This paper focuses on a jacket-type substructure, which is the second most common substructure type in European offshore wind farms, alongside monopiles [16]. With respect to structural integrity, the welds of the tubular joints are the most critical locations for fatigue.

In the design stage, lifetime calculations of the substructure are based on the as-designed geometry and idealized welds. High safety factors are included to account for the deviations of the as-built geometry. By performing a more detailed analysis of the tubular joints, the lifetime can be assessed more accurately and lower safety factors can be incorporated. Previous research [11, 6] has shown that the actual weld geometry significantly influences the local stresses and, consequently, the fatigue life. This work aims to develop a new method for fatigue life analysis that accounts for the as-built geometry of the welds and any surface degradation due to (pitting) corrosion, based on 3D laser scans of the joints.

2 Literature study

In 2016, Lang et al. [8] applied 3D laser scanning for the quality assessment of welds. They highlighted that using 3D laser scanning, the quality control can be done independently from the operator, resulting in greater

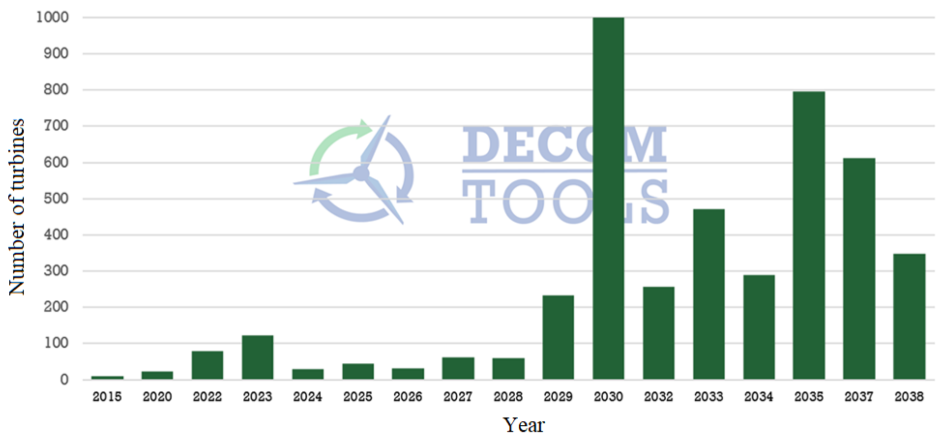

Figure 1: Number of wind turbines that reach their design lifetime in the North Sea [10].

consistency. In a follow-up paper, they showed the potential of using laser scanning data as input for finite element models for fatigue analysis [7]. Inspired by Tovo et al. [15], Lang et al. applied the stress gradient approach to determine fatigue governing effective stresses. These were then used as input for a probabilistic Weibull-based crack initiation framework to calculate the fatigue life of a variety of components.

Stenberg et al. [13] investigated the use of laser scanning technology for online monitoring of weld quality. They developed a system called ONWELD to assess the weld quality of fillet, overlap, and butt welds. A few years later, Hultgren et al. [2, 4, 3] from the same research group published several papers on the fatigue assessment of welded joints based on data collected from laser scans. They evaluated the importance of variations in the weld geometry features, such as weld toe radius, weld toe angle and throat thickness, on the fatigue strength. They used a probabilistic framework focusing on the weld geometry features to evaluate the fatigue strength. One of the conclusions drawn from their work was that surrounding geometry can reduce the influence of a very small local defect. The main advantage of using laser scanning data is thus also the biggest challenge of the technology, namely that much smaller defects can be detected compared to weld property measurements.

Shojai et al. [12] investigated the influence of pitting corrosion on the fatigue strength of steel structures. To quantify the corrosion damage, they used 3D surface scans. The influence on the local stress of the pitting corrosion is captured with stress concentration factors. These can then be used for the evaluation of the remaining fatigue life based on S-N curves. In previous research at Laboratory Soete, finite element models haven been generated based on 3D scans of corrosion pitted surfaces [5]. The result of such an analysis is shown in Figure 2. The main challenge faced in this research was the convergence of the local stress values at the sharp features of the model.

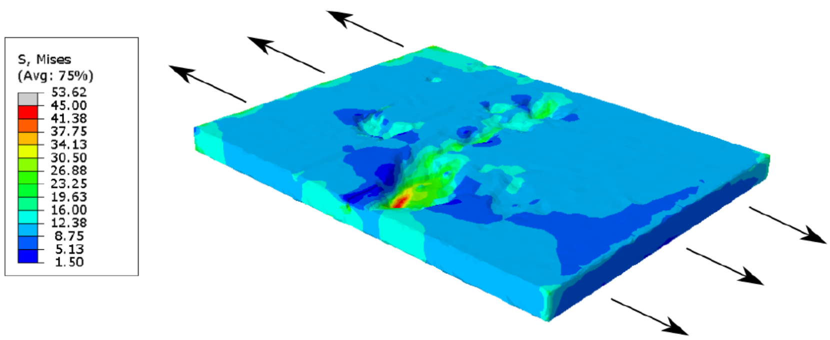

Figure 2: Distribution of von Mises stress in a finite element model based on a 3D scan of a corrosion pitted surface [5].

3 Methodology

First, a 3D scanner is used to capture the geometrical data of tubular joints. In this work, the Creaform HandySCAN3D is used, which projects structured blue light on the surface of the specimen. The deformed pattern is observed by two cameras and is used by the software to recreate the outer surface based on the triangulation principle. The output of the scan is a point cloud.

The downside of laser scanners is that only the outer surface can be scanned. Besides, only the outer walls of the tubular members are accessible. Therefore, a framework is developed to (semi-)automatically reconstruct the inaccessible parts of the specimen. This requires assumptions to be made about the inner walls of the tubular members and the geometry of the weld roots. The reconstruction steps followed by the framework are shown in Figure 3.

The reconstructed point cloud forms the basis for a finite element model. The finite element models of the joints include as much geometrical detail as possible. However, it is expected that stress singularities will occur at sharp features in the finite element model.

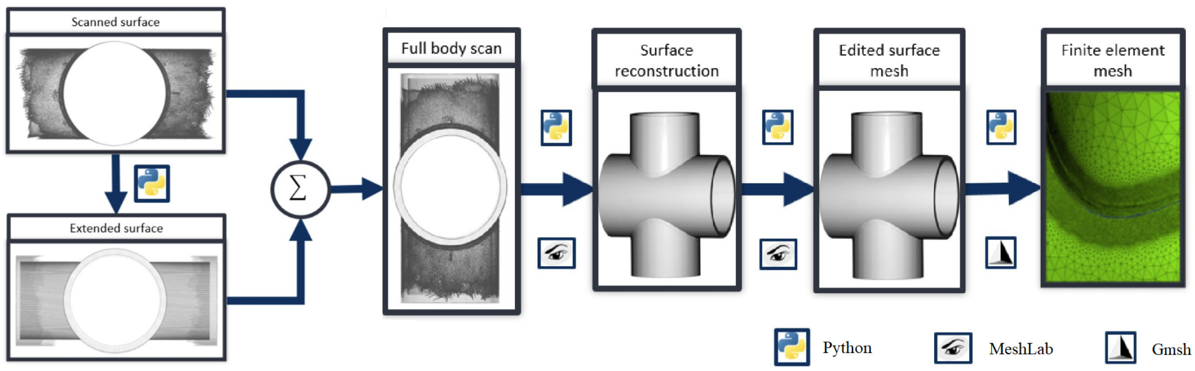

Figure 3: Flowchart illustrating the process of mesh reconstruction from 3D scan data.

To deal with the stress singularities, different stress analysis methods will be compared, such as the theory of critical distances (TCD) [14] and the implicit gradient approach [15]. The results of these stress analysis methods is an effective stress, which is not sensitive to the stress singularities. Especially, the implicit gradient approach seems promising since it is a non-local method. This means it can be applied to the whole specimen at once, contrary to the more popular TCD variants.

Appropriate loading conditions for the high-fidelity tubular joint models will be determined from global aero-hydro-elastic simulations on a full-scale lower-fidelity model. Within the scope of this work, these simulations will be performed in the QBlade software [9]. These simulations will be used to determine the loads on the members of the studied joints, which can then be applied to the high-fidelity joint models.

4 Expected outcomes

The expected outcomes of this research are:

- The development of a numerical framework that is able to convert welded joint scanning data to highly detailed solid finite element models. The 3D scans are made with a handheld laser scanner.
- The development of a stress-based fatigue analysis method for long continuous welds of tubular joints based on surface scanned data. The output of this method is an effective stress, which can be used together with S-N curves to determine the remaining fatigue lifetime of the joint.
- Hindcasting the accumulated fatigue damage and forecasting the remaining fatigue life of offshore jacket structures. To this end, the high-fidelity submodels of welded tubular joints will be one-way coupled to aero-hydro-elastic global models.

The expected outcomes of this research will contribute to the advancement of knowledge in the field of fatigue damage accumulation of welded tubular joints, leading to improved design practices and lifetime calculations for offshore jacket substructures.

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