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WRAPPED COMPOSITE JOINTS FOR FATIGUE RESISTANT CIRCULAR HOLLOW SECTION STEEL STRUCTURES IN WIND ENERGY

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Abstract
Offshore renewable energy sources, such as wind and solar require resilient support structures that are vastly loaded by cyclic loading due to wind and waves. As such, the structures built from steel circular hollow sections are structurally optimal to resist extreme loads but their design is hampered by low fatigue resistance of traditionally welded joints resulting in short lifetime, excessive use of steel material and corrosion problems. Innovative wrapped composite joints connect steel tubes by bonding and replace traditional complex welded joints of tubes by relying on excellent corrosion and fatigue performance of fibre-polymer composite material. Composite joints can reduce amount of steel needed to build supporting structures prone to fatigue up to 50% and can speed up production and assembly of towers supporting wind turbines by factor of 2. In addition, the wrapped composite joints unleash the potential of designing and building corrosion free offshore support structures completely made of composite tubes as structural members, or in combination with steel tubes. This paper presents potential of wrapped composite joints, state of development through experimental testing and numerical modelling, certification of joints and pilot projects in offshore environment. The outlook for further research and development is also given.

1. Introduction

For the Dutch 'Klimaatakkoord' and for the rest of EU the most important target is a 55-60% CO_2 emission reduction in 2030 compared to 1990 [1]. Wind energy and especially offshore wind plays an important role in energy transition targeting 55-60% CO_2 emission reduction in 2030 compared to 1990 [1] in EU. For example, the targets of the Dutch government are set to cover 40% of the current electricity production via offshore wind and to have a resulting installed capacity of 21GW in 2030 [2].

Figure 1. Traditional Welded joints used in multi-membered jacket offshore wind turbine support structures

To reach these goals the levelized cost of energy (LCOE) of offshore wind applications needs to be reduced further. Increasing the design life of wind farms is seen as one of the most promising innovations with the largest cost reducing impact but reducing the needed operation and maintenance (O&M) also has a potential significant optimisation. Besides cost reduction in general, alternative technologies for enabling the installation of XXL wind turbines in deeper waters is needed since close to 80% of the world's offshore wind resource potential is located in waters deeper than 60 metres. The dominance of the monopile as preferred foundation type will therefore decrease, as the weight of the monopile for future installed capacities of over 14MW in water depths of over 40m already have a mass of 2,000 - 3000 according to [3]. To reduce the cost of support structures as well as the carbon footprint (80% of the carbon footprint of a monopile is generated by steel) an overall reduction in steel consumption is an effective measure. Jacket structures are one of the alternatives that are well suited for deeper water and larger wind turbines. Use of Jackets would also lead to less steel usage (steel reduction of 30-50% compared to monopiles). Jacket structures have one of the best steel/stiffness ratios but face the challenges in the economical design and manufacturing speed/capacity due to the use of unfavourable welded joints, see Figure 1. Corner welds reduce the fatigue resistance of structural joints of circular hollow sections (CHS) with factors that results in increased wall thicknesses of the tubes and overspending of the multi-membered part of the steel jacket of approximately 80%. The current speed of production of jacket structures is a challenge as the production capacity in terms of numbers of jackets per year do not fulfil the needs of the market. Bottlenecks are complex welds that need to be made in the production yard and coating.

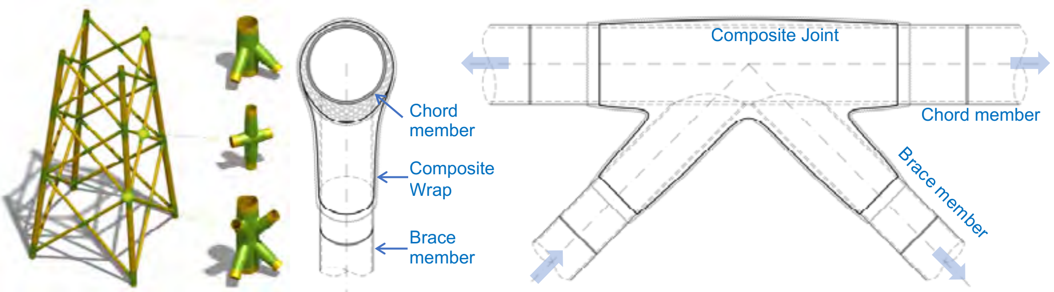

Figure 2. a) Visualization of offshore wind turbine jacket supporting structure with wrapped composite joints; b) Schematics of a wrapped composite joint type K-joint.

If the fatigue resistance for these joints can be increased, the wall thicknesses of the legs (chords) and brace members can be reduced resulting in significant lighter structures. If the complex joints can be prefabricated the production rate of the jackets structures can significantly increase.

TU Delft and Tree Composites, together with their partners, are researching the behavior the wrapped composite joint to solve this challenge for lattice type welded structures. The breakthrough of the concept is that the load is transferred through a dedicated composite wrap and not trough the small surface of the weld. The brace members (diagonals) are bonded to the chord members (legs) through a coupling formed by a sufficiently large composite wrapping, see Figure 2. The composite wrap is tailored (length and thickness) to deal with static and dynamic loads transferred by the joint. The optimized, nature-like, shape of the composite wrap, with increasing thickness towards the root of joint, reduces the stress concentration in the composite material and bonded interface, thereby solves issues in fatigue prone/driven design. The tailorability of the composite wrap provides potential to design for longer lifetimes with minimal increase in thickness and length of the wrapping. The substantial improvement of the fatigue endurance of the CHS joints is achieved by completely circumventing stress concentrations in steel CHS due to local wall bending, and avoiding residual stresses, embrittlement and notch effects due to welding. This results in huge reduction of thickness of CHS members resulting in multi-membered structure weight reduction up to 50%. Note that the wrapped composite joint is aimed to replace all welds in different types of joints such as T, K, Y, X, Double-K and splice joint geometries which can be found in offshore wind structures (floating and bottom founded)

2. Performance of Wrapped Composite Joints

Initial studies at TU Delft form 2018 to 2020 demonstrated 3 main advantages of wrapped composite joitns over traditional welded joints through more than 80 lab joint experiments and numerical analyses. At first, static loads higher than yield resistance of the CHS profiles at the small-scale (ø60 mm), can be achieved [4] in axial tension, comperesion and bending resistance of the joints. Secod, the fatigue endurance of wrapped composite joints was found to be superior vs. welded when subjected to axial tension loads which is the most critical for debonding [5], showcasing that wrapped composite joints have potential to even outreach fatigue life of non-welded steel tubes for the diameter to thickness ration of the tubes used in the offshore wind jacket support structures. Third, better fatigue performance was observed on small-scale joint specimens subjected to accelerated seawater ageing vs. reference speciemns ar room conditions. As follow-up of such well demonstrated performance, WrapNode project was initiated with help of Dutch Ministry for Entrprenuralship (RVO). The first phase of the project (2021-2024) was focused on assessing three most unknowns related to the behaviour of the joints to be applied in offshore wind support strucutres. Those are: durability in offshore environement, multiaxial behaviour of the joints and upscaling behaviour of the joints.

2.1. Durability of the wrapped composite joitns in offshore environement

No degradation, nor reduction of extreme load resistance and fatigue performance was observed from the WrapNode joints subject to seawater ageing compared to reference non-aged joints , Composite layers employed in WrapNode production show excellent water resistance and corrosion protection for steel tubes. Remarkable fatigue endurance was exhibited under sub-zero temperature (-10˚C), with only a slight reduction in fatigue life observed at elevated temperatures (+50˚C and +70˚C) compared to joints at room temperature. No significant disparities were identified in extreme load resistance w.r.t. sub-zero or elevated temperatures. Wrapped composite joints clearly demonstrate potential for even further extended fatigue life in low temperature conditions (such as offshore) where traditional welded joints are known to suffer reduced fatigue life due to limited toughness of the welds at low temperatures.

2.2. Multi-axila behaviour of the wrapped composite joints

The impact of combined (multi-axial) loading on the extreme load resistance and fatigue performance of wrapped composite joints was investigated in unique Hexapod testing rig in Stevin 2 lab at TU Delft and by advanced numerical models. The primary finding indicates that the wrapped compoite joitns resist well the multi-axial loading with not result in significant reductions both static and fatigue performance compoared to uniaxial load cases. Quite significant resistance to bending loads were found in those lab-scale joint experiments, in fact the steel tube yielded outside of the joint region.
The joints were further tested with the most complex (multi-axial) geometry, the KK-joints that come from the corners of the jacket support structures. Tests were performed in specially built 250t capacity testing frame in the Stevin 2 lab. The results of the tests and comparable finite element analysis concluded that no reduction of extreme load resistance nor fatigue performance is owing to increasing complexity of the joints' geometry.

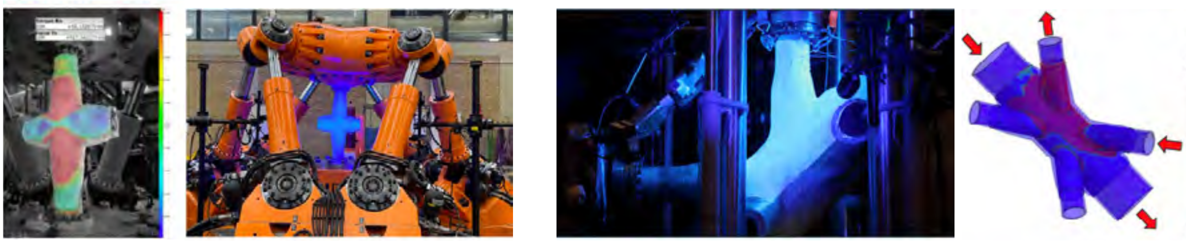

Figure 3. Multi-axial loading test in Hexapod (6 DOF test rig) and tests on KK joints (multi-planar).

2.3. Upsacling behaviour of the wrapped composite joitns

The results from the full-scale static tensile tests on representative joint indicate that the interfacial bond resistance between the steel and composite surpasses by 22% the yield resistance of the reference steel brace member (ø660 × 16 mm) in the middle bay of the full-scale jacket, specifically designed for supporting the 14 MW turbine in 40 m deep water. This means that the innovative wrapped composite joints can be successfully designed and manufactured to reliably survive most severe storm conditions for offshore wind turbine support structures. Also, the full-scale joint remained intact during cyclic (fatigue) testing at the design load level corresponding to the fatigue load in the joint from the turbine operation and waves for 25 years ifetime. Furthermore, the joint withstood 1.8 million cycles at an “beyond extreme” cyclic load level (3 times the design fatigue load). In other words, the longevity of the full-scale joint at the design load level is estimated to be 880 thousand years of lifetime which means that after 25 years of operations less than 1% of the composite joint fatigue life is consumed.

3. Conclusions and outlook

Wrapped Composite Joints are made by applying FRP composite in region of complex joints of CHS tubular members and completely replace the complex welds. With their remarkable fatigue performance the open new horizons for reducing LCOE and CO2 emissions of support structures of offshore wind turbines.

- The remarkable fatigue resistance of the composite joint enables a substantial reduction in the use of steel in offshore renewable foundations. This not only promotes a more sustainable approach to material usage but also facilitates more cost-effective foundation design, necessitating smaller and economically viable installation vessels.
- The exceptional fatigue performance of wrapped composite joints opens avenues for unprecedented designs and optimization of jacket support structures for offshore wind, particularly beneficial for floating support structures that are more susceptible to fatigue influences.
- With fatigue concerns mitigated in the connection of tubular members, the utilization of high-strength steel becomes feasible, allowing for the realization of its full-strength potential. Furthermore, the integration of hybrid structures becomes achievable through the use of wrapped composite joints.

Certification of the desing and manufacturing of the joints in cooperation with DNV is ongoing since 2020. First full scale structure was deployed in 2023 as demonstraton project to support solar panels at sea where wrapped composite joints were utilized to make complete floaring platform strucutre from FRP tubulars.

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