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Full scale testing of fatigue resistant composite joints for offshore wind Jacket and Floating structures

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Abstract. Complex welds in the joint region reduce the fatigue resistance of structural joints of circular hollow sections with factors that results in increased wall thicknesses of the tubes and overspending of steel in the multi-membered part of the jacket and floating support structures for offshore wind turbines. The wrapped composite joint is a breakthrough technology utilising bonding and fatigue resistant composite material to connect steel tubular members instead of welding. The main technical advantage is that the superior fatigue life of wrapped composite joints. Full-scale wrapped composite joint is tested by cyclic out-of-plane bending loading in resonance-based Cronos testing rig at OCAS N.V. in Belgium. Results reveal exceptional fatigue life of wrapped joints to combined loading when compared to welded joints, showcasing a potential that can radically reduce steel use for offshore structures.

1. Introduction

Foundations for offshore Wind Energy Convertors are dominantly made with monopiles. Jackets is an alternative foundation utilizing structural efficiency of Circular Hollow Sections (CHS, a.k.a tubes) in multi-membered structure, but is facing challenges in terms of costs and manufacturing speed. The dominant design criterion for foundations is fatigue. In the case of jackets, large stress concentrations factors at the tubular joints are requiring larger member thickness. If the stress concentrations at the welded tubular joints could be reduced, a significant thickness reduction could be applied, up to 50%.

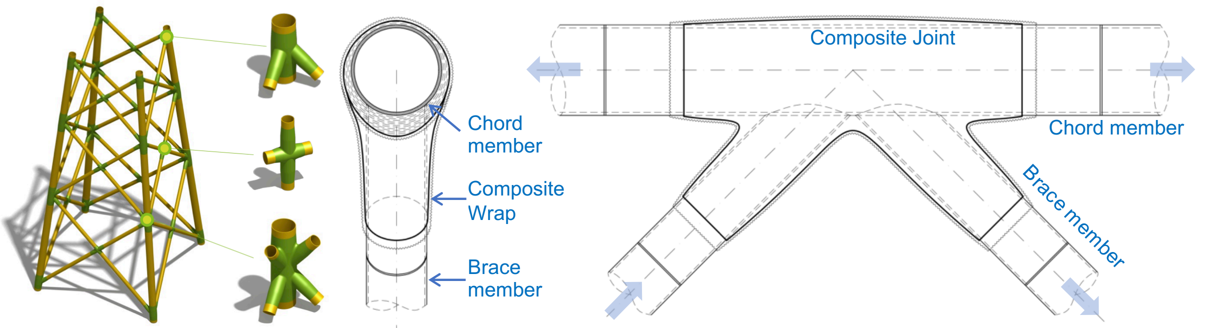


Figure 1. a) Visualization of offshore wind turbine jacket supporting structure with wrapped composite joints; b) Schematics of a wrapped composite joint type K-joint.

If the fatigue resistance for these joints can be increased, the wall thicknesses of the legs (chords) and brace members can be reduced and can sections in joint regions can be omitted, resulting in significant lighter structures. If the complex joints can be prefabricated the production rate of the jackets structures can increase by 50-100%.

TU Delft and Tree Composites, together with their partners, are investigating the behavior of wrapped composite joints 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 section 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 1.

Within the WrapNode-I project (2021-2024) financed by Dutch Ministry of Enterprise (RVO) the full-scale wrapped composite joints are tested and understood under influence of multi-axial loads and offshore environment and the technological and economic feasibility in offshore jackets is validated on critical points. Project is led by TU Delft conducting experimental and numerical research with Tree Composites B.V. as largest executing partner developing engineering and production of composite joints, and other contributing partners: HSM offshore, Enersea, AOC, Siemens Gamesa Renewable Energy, Parkwind, Shell and Vattenfall. Project aim is to develop wrapped composite joint that in full-scale and offshore environment will have static and fatigue resistance exceeding the resistance of the steel jacket tubes that it connects.

The paper presents the first full-scale tests of wrapped joints that was recently performed. First, the specimen design will be presented, followed by the experimental set-ups. Then the results of the tests will be presented and discussed. This paper also presents estimation of fatigue life of an equivalent welded joint for comparison reasons, as well as overview of validation of wrapped composite joints for static loads and multi-axial behavior and outlook for future research.

2. Specimen design and manufacturing

One full-scale X-joint with a 90° angle, see figure 2, was prepared to investigate the fatigue performance of a wrapped joint. The specimen length was 12 m. The braces were chosen to be sufficiently long to obtain an adequate resonance frequency and limit the shear forces. Glass Fibre Reinforced Polymer (GFRP) composite wrap was used to make the composite joint. There was no welding involved in connecting the steel tubes. The composite wrapping length was close to 3m.

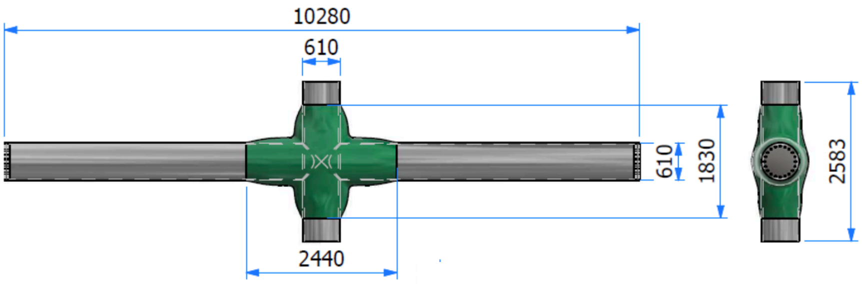


Figure 2. Full-scale wrapped composite joint geometry.

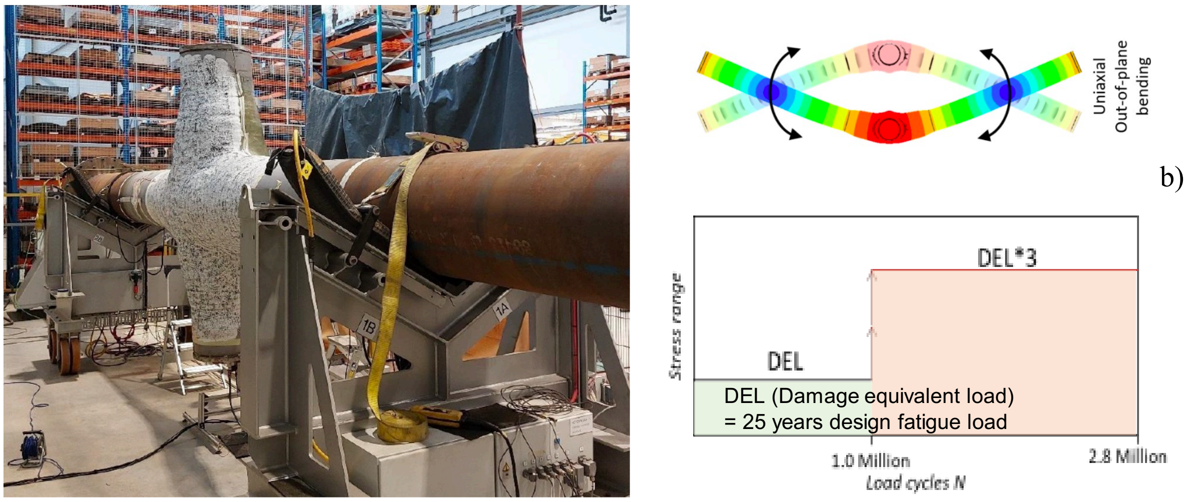
Figure 3. Full-scale specimen of wrapped composite joint after production presenting the X-joint of braces in offshore wind turbine jacket supporting structure.

The full-scale 90° wrapped X-joint was designed based on a case study design for a representative jacket foundation supporting a 14MW turbine and located in the North Sea, off the coast of the Netherlands in a water depth of 40 meters. The structure uses tubes of 610 diameter and 16mm thickness for the braces and chord. To enhance the fatigue life of the specimen steel tubes and prevent fatigue failure prior to damage of the composite wrap, the design was modified, using ø610x25mm tubes. Figure 2 illustrates the geometry of the full-scale sample. The maximum composite thickness at the center of the joint was approximately 150mm. Figure 3 shows the full-scale specimen after production.

3. Experimental set-up

The fatigue test was performed in the Cronos test rig at OCAS, Belgium. The principle of loading is to excite the specimen by a loading at a frequency close to the specimen eigen frequency. Shakers are positioned at the specimen's ends generating the excitation force. More details about the development and operation of the of the set-up and utilization in testing of welded tubular joints can be found in [1], [2] and [3]. The orientation of the excitation was chosen to be out-of-plane, which is controlled by selecting the direction of the shaker's excitation, see figure 4a and figure 4b. The amplitude of the loading was controlled by measuring the strain amplitude measured on the braces and adjusting accordingly the excitation frequency. The specimen is supported at the positions where the eigen mode is not causing any displacement. In this specific case, the test was performed with an out-of-plane excitation.

The specimen denominated X90-Fs-FLS was subjected in total to 2.8 million cycles. The first 1 million cycles of damage equivalent load (DEL) corresponds to 25 years operation of the turbine and the support structure subject to wind and waves. The latter 1.8 million cycles were tested with tripled load (corresponding to storm load level), see figure 4c for loading regime that was applied. The trippled load was applied with the motive to push the join to the limits and impose damage that can later be used to estimate the total life and validate numerical models for damage prediction in a later stage of the research program.



a) c)

Figure 4. a) Test setup of full-scale joint specimen X90-Fs-FLS subjected to out-of-plane bending fatigue test; b) Loading priniciple; c) Load history of the fatigue tests given stress range of DEL and tripled DEL.

3.1. Damage Equivalent Load

The constant amplitude damage equivalent load (DEL) on the joint was calculated based on load histories generated for the full-scale jacket design in 40m deep water supporting 14MW turbine. The load histories result in combination of variable joint loads in form and axial forces and in-plane and out-of-plane bending moments. However, only bending load can be applied in the Cronos set-up. To this end, the relevant combination of the design FLS axial forces and bending moments on the join were converted to a constant amplitude out-of-plane bending load that has equivalent damage as the variable amplitude multiaxial load combination. The damage equivalence was based on strain energy release rate (SERR) at the debonding crack front inside the joint which was calculated using Finite Element Models and VCCT approach in Abaqus software package [4]. For the analyzed joint the resulting constant amplitude damage equivalent load (DEL) applied through out-of-plane bending moment was found to be 250 kNm for 1M cycles.

3.2. Measurements set-up

Fatigue experiments on full-scale were supported by real-time 3D Digital Image Correlation (DIC) measurements. DIC was utilized for global deformation and surface strain measurements. Two GOM Aramis adjustable systems and one GOM Aramis SRX system equipped with two 12- megapixel cameras were used. The 3D DIC measurement technique indirectly identifies debonding between the steel and FRP by measuring surface strains, as suggested by He and Pavlovic [5].

The adjustable systems were positioned to capture each brace, while the SRX system was placed to measure the chord. Measurements were taken at the maximum and minimum bending moments during the experiment. The arrangement of the DIC systems is shown in figure 5. The SRX (high-speed system) positioned in the middle, captured 6 pictures at the top of the load cycle and 6 pictures at the bottom of the cycle. Based on the time delay between the first picture and the picture at the top of the cycle, the adjustable systems (normal-speed systems) were triggered to take only one picture at the top and bottom of the load cycle. This sequence was repeated every 100 seconds (equivalent to approximately 1500 cycles). The sequence is illustrated in figure 6.

Figure 5. Three 3D DIC systems measuring displacements and strains simultaneously during cyclic test at 15 Hz.

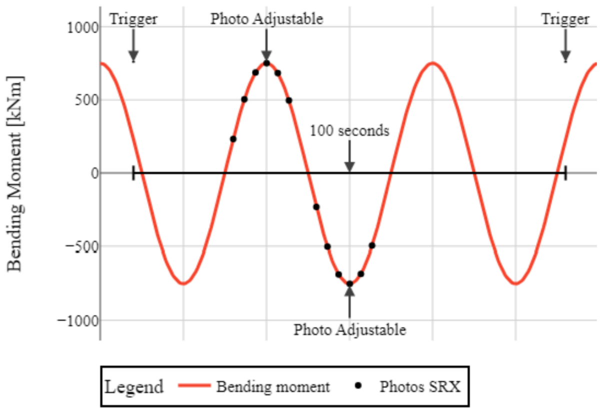


Figure 6. Measurement sequence imposed to DIC systems during full-scale experiment to capture the peak load points without stoping the test.

3.3. Full-scale FLS testing protocol

In total the FLS test lasted for 3 weeks in period of February and March 2023. The test was performed under supervision of an operator. Hence the test was paused overnight and during the weekend. The FLS test was divided in 3 separate stages defined below:

- In Stage 1 the constant amplitude load level corresponded to the design Damage Equivalent Load (DEL) of an offshore wind jacket structure with a 25-year design life. For the FLS sample geometry this DEL corresponds to 1 million cycles at 250 kNm bending amplitude. Considered on the level of a equivalent welded steel joint the maximum bending stress (amplitude) in the centre of the joint would be 39 MPa.

- In Stage 2 the load amplitude was multiplied by a factor of 3, roughly corresponding to ULS design load i.e. the storm load level with 50 year return period. The sample is cycled for 1.8 million additional cycles and is stopped when a crack started propagating through the surface of the composite wrap. The 3x250=750 kNm bending amplitude corresponds to a maximum bending stress amplitude of 116 MPa.
- Stage 3 was performed at the same loading amplitude as Stage 1 for 170 000 cycles to investigate the behaviour of the sample at the FLS design load level in presence of the crack that appeared in Stage 2.

In stage 1 the test was interrupted several times for inspections, adjustments and overnight stops. The testing frequency at the start of the Stage 1 test was 14.9 Hz which is about 1 Hz below the theoretically calculated value for the eigenfrequency of the out-of-plane bending mode. At the end of Stage 1 the excitation frequency was slightly reduced to 14.8 Hz which might have been caused by a small stiffness reduction due to limited self-heating.

The stage 2 loading with three times higher testing amplitude required higher starting testing frequency of 15.2 Hz because stiffness degradation of the specimen was expected. During inspection of the paused test, it was noticed that the FLS sample outside temperature had increased. The increased temperature will have caused a certain stiffness reduction which resulted in a frequency drop and a deflection increase. The testing procedure was altered, and the outside temperature of the specimen was monitored using an infrared thermometer and a thermographic camera. The test was interrupted more frequently, and pauses are introduced allowing the sample to cool down. During the test intervals of Stage 2, the testing frequency gradually decreased. Over the total duration of the test a decreasing trend of the test frequency and an increasing trend of the displacement amplitude was visible indicating a stiffness reduction likely related to internal damage at the steel-composite bonded interface and in the composite wrap.

4. Full-scale FLS test results

4.1. Stiffness degradation

After 1 million cycles of the DEL load (stage 1), no stiffness degradation was observed as shown in figure 7a. The conclusion is that the load level corresponding to damage equivalent load results in no damage. As expected, the tripled load level of stage 2 resulted in stiffness degradation and limited damage. Stiffness reduction results at tripled DEL are shown in figure 7b. After the 1.8 million cycles at the increased load level, the measured stiffness decreased by by 11% with no signs of loss of structural integrity of the joint.

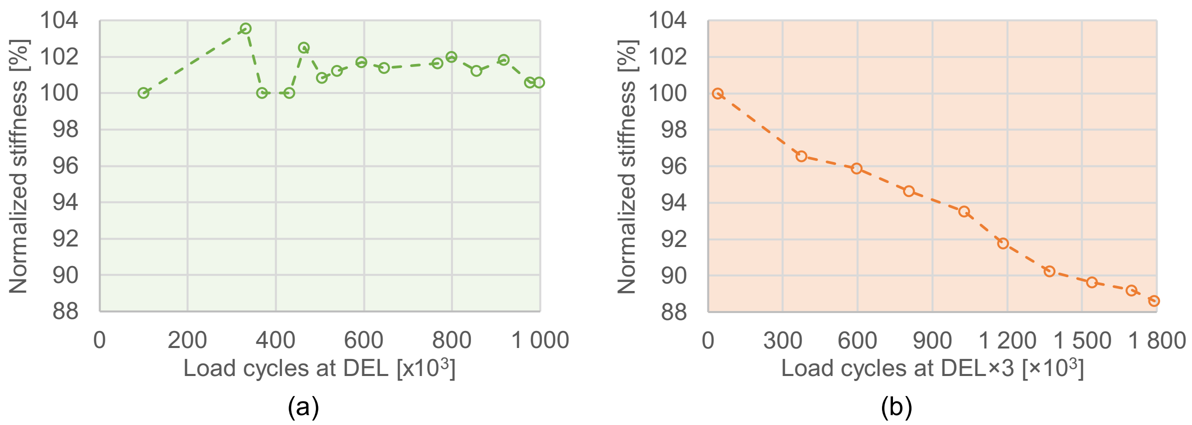


Figure 7. a) Bending stiffness in the first 1 million cycles of DEL;b) Bending stiffness in the lateral 1.8 million cycles of tripled DEL.

4.2. Interpretation of full-scale wrapped composite joint FLS test result

Stage 1 loading, corresponding to design load of 25 years operation of the structure supporting 14MW turbine, shows no signs of damage. The estimation is that the fatigue life of the joint at this load level is below threshold of damage initiation and therefore able to practically reach the cut-off limit, i.e. to have infinite fatigue life. This is attributed to to favourable fatigue crack retardation that is found in wrapped composite joints on smaller scale as presented in [6]. Further estimation of the fatigue life at the design FLS load level, with help of literature published on wrapped composite joints so far, is given in chapter 4.2.

The full-scale joint survived at least 1.8 million cycles in test with loads ranging from +750kNm to -750kNm. During the first 1 million cycles of the increased load the stiffness degradation is primarily driven by steady debonding crack growth between the steel CHS brace members and the composite wrap. Subsequently, in the next 0.8 million cycles, a through-thickness crack initiated in the composite material. The total life of the joint in this case was considered to be 1.8 million cycles, even though complete failure of the joint was not reached.

To prove that the structural integrity of the joint is still at very high level the flow-up loading in stage 3 was corresponding to FLS design load level, i.e. +/-250 kNm. During the stage 3 loading there were no signs of further propagation of the identified surface crack, nor stiffness degradation over additional 170 thousand cycles.

5. Comparison of wrapped composite and equivalent welded joint performance

An analysis was performed for a welded joints, considering the same loading scenario as the one applied for the tested wrapped joint. The goal is to analytically reproduce what would be the fatigue life of the equivalent welded joints if they were tested under identical loading conditions and setup. In the first instance I load range considered for the comparison to the welded joint corresponds to loading stage 2 of full-scale FLS test of wrapped composite joint. Only at this very high load level it was possible to impose damage and test the fatigue life of the wrapped composite joint. Ithe appearance of the surface crack after 1.8 million cycles of stage 2 loading in the test of the wrapped composite joint is considered as conventional end of life to be compared to fatigue life estimate of the equivalent welded joint. Therefore, the bending moment amplitude of 750 kNm, with fully reversed load (R=-1), was used to estimate fatigue life of the equivalent welded joint. Here the equivalent is considered to be the welded joint that has the same diameter and thickness of the tube as it was the case for the tested wrapped composite joint. The out-of-plane bending moment range is therefore 1500 kN that leads to the nominal stress range at the joint root of 232 MPa for the tube diameter 610 mm and thickness 25mm.

5.1. Fatigue Life Estimation of equivalent full-scale welded joint

Fatigue life estimation of the equivalent full-scale welded X-joint is done according to the Hot Spot stress approach in accordance with DNV-RP-C203 [7], using the T-curve (tubular joint in air)]. HowI, the S-N curves provided in DNV-RP-C203 [7] are the characteristic S-N curves, namely reduced towards 2.3% percentile to account for uncertainty. For a fair comparison between the fatigue life of wrapped composite joint obtained by test and the fatigue life of the equivalent welded joint obtained by calculation , the average curves, not the characteristic ones need to be used for calculation of fatigue life of welded joints at the load level of +/-750 kNm. The S-N curves provided in DNV-RP-C203 [7] originate from fatigue tests on offshore tubular joints summarized in OTH-92-390 [7]. Therefore, the average S-N curves from OTH-92-390 [8] are used. The average S-N provides approximately 3 to 4 times longer fatigue life than the characteristic curve.

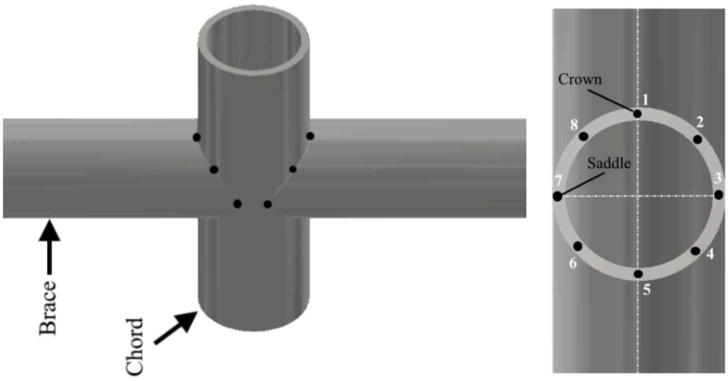


Figure 8. Hot spot stresses extraction points for equivalent welded joint.

For the equivalent welded full-scale joints, the hot spot stresses can be determined as the nominal stresses in the connection, multiplied by a corresponding stress concentration factor (SCF), calculated using empirical equations as per DNV-RP-C203 [7]. In general, the hot spot stresses are evaluated in 8 different points around the joints circumference, including the crown and saddle positions as depicted in figure 8. The corresponding SCF for the joint loaded by out-of-plane bending SCFs are calculated for the saddle location at chord and the brace, $SCF_{\mathrm{MOP,br}}$ = 1.42 and $SCF_{\mathrm{MOP,ch}}$ = 2.68, respectively. The critical location is the weld toe at the saddle location on the chord, resulting in hot spot stress of 624 MPa due to the range of the out-of-plane bending moment of 1500 kN. The c□tilizinactise in offshore welded jackets is that the welds connecting braces to chords and braces to braces in X-joints are made as double-sided to prevent weld root crack which is difficult to predict and has very poor performance. The welds are made from both outside and inside of the full-scale joints composed of short cans. Decision to use single or double-sided welding is project specific and can depended on tube diameter, SCFs, etc. In this comparision the the assumption is taken that the welded joint is made with double-sided welds to have as long as possible fatigue life.□tilizinI The hot spot stresses are highest at the weld toe on the outside of the weld. Using the average T curve from the S-N curves provided in OTH-92-390 [8],the fatigue life for the stress range of 232*2.68 = 624 MPa is only 26.055 cycles. This is the estimated life of an equivalent joint of same diameter and thickness of the tubes with double sided welds if it would be tested under the same +/- 750 kNm cyclic load as the tested wrapped composite joint.

5.2. Discussion of the results

The fatigue life of the tested wrapped composite joint at +/- 750 kNm out-of-plane bending moment range is at least 1.8 million cycles. The estimated fatigue life of an equivalent welded joint with same dimeter and thickness of the tube (ø610x25mm) is 26 thousand cycles. The conclusion is that wrapped composite joint has 70 times longer fatigue life.

Such substantial improvement of the fatigue life demonstrated by the wrapped composite joints is based on comparisons at a very high load level, the tripled damage equivalent load that approximately corresponds to the ULS loads, or in other words to a storm with 50 years return period. Such high load level was chosen in order to be able to impose damage in full-scale wrapped composite joint fatigue test. Much lower load levels, factor 3 to 5 lower, are representative for actual cyclic loading in the real joints of tubular members in offshore structures. For example, the damage equivalent load in this study is 3 times lower. Feng and Pavlovic [9] showed that the expected slope of the S-N curve of wrapped composite joints is in range of m=8 to m=10. Comparably the slope of the S-N curve of welded joints according to state-of-the-art research and design codes such as DNV-RP-C203 [7] is in range m=3 to m=5. This means that the difference in the fatigue life of wrapped composite and welded join would be even bigger at the lower, realistic fatigue load levels. Rough estimate of such difference can be made based on the slopes of the S-N curves and the fatigue life difference found in this study. The estimate of the fatigue life difference is extrapolated to the damage equivalent load which is 3 times lower than the tested load to depict this. For the sake of comparison, the slope m=8 and m=4 is assumed for wrapped composite and welded joints, respectively. The estimated fatigue life of wrapped composite joint at the lower load level would be 11,8·10^9 cycles (=1,8·10^6 ·3^8). The estimated fatigue life of welded joint at the lower load level would be 2,11·10^6 cycles (=26,055·10^3·3^4). The wrapped composite joint would have approximately 5.000 times longer fatigue life that the equivalent welded joint at the load level corresponding to DEL in this study, or in terms of stress range, at a load level corresponding to 68 MPa nominal stress in the brace member. This shows that transferring loads trough composite material is far superior and that steel consumption in the jacket can be optimized. Such result opens new ways of thinking about design of jacket structures and opens ideas on re-use and re-purpose of full structures. Fatigue life of joints in jacket made with composite wrapping have potential to reach cut-off limit, i.e. infinite fatigue life. Threfore, jacket structures with lifetime of 100 years or more are thus possible without any or small weight increase.

6. Validation of wrapped composite joints static resistance at full-scale

Two full-scale X90-joints joints were loaded in uniaxial tension to investigate the static performance in the ultimate limit state. Figure 9 shows the test setup of the full-scale joint specimen. To investigate the interfacial bond capacity between steel and wrapped composite, the design thickness of steel braces in tension was increased from 16 mm to 25 mm to avoid steel yielding. The ULS tests are carried out in the OCAS Tubular Testing System (TTS). This test rig has a capacity of 1580 kN (3.5 Mlbs) in both tension and compression. The system is installed in an explosion-resistant testpit which allows for safe operation given the high loads that are applied. In case of tubular test specimen the system allows for testing with high internal liquid or gas pressures, but this is not utilized in X90 full scale wrapped composite joint ULS test.

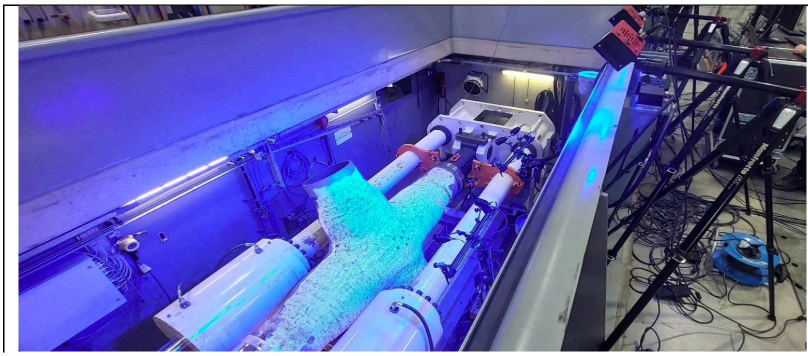


Figure 9. Test setup of full-scale specimen X90-Fs-ULS-01 in the test pit with blue light for 3D DIC cameras used for real-time full-filed strain and displacement measurement.

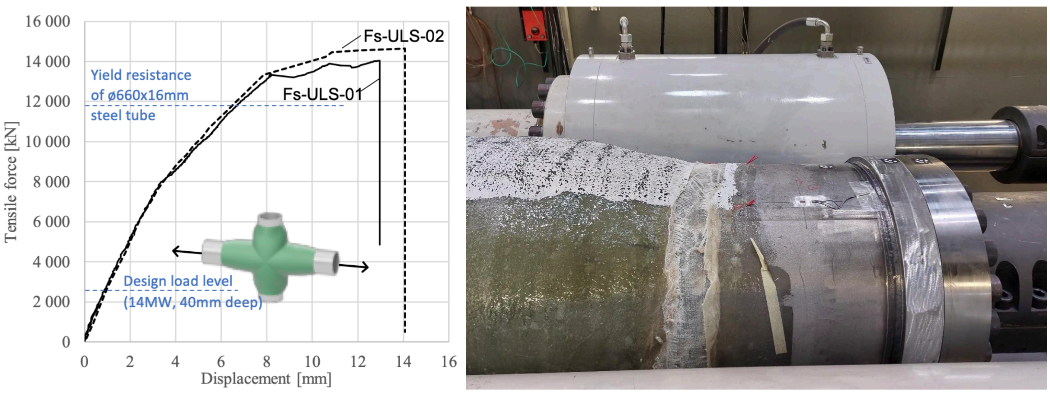


Figure 10. Static performance of two X90-Fs joints in uniaxial tensile tests with the imposed debonding failure.

The static tensile tests show that the interfacial bond capacity between steel and composite could reach 14.4 MN on average which is 22% higher than the yield resistance of the reference steel brace member (ø660 × 16 mm) in the middle bay of full-scale jacket designed specifically in the project to support 14 MW turbine in 40 m deep water. Figure 10 shows the load-displacement curves of the two specimens tested and the failure mode dominated by debonding which results in pull-out of the steel tube form the composite wrap.

7. Outlook of the development of the wrapped composite joints

In summary, the result of the presented tests in this paper demonstrate that the wrapped composite joint can outperform fatigue performance of complex welds. Testing is followed by the development of finite element and analytical based prediction models that show very good predictions of joints performance across the scales and for different load directions.

Research under the WrapNode-I project focuses on de-risking the most unknown failure mode of the wrapped composi–e joints - the debonding of the steel-composite interface. To this end, all the test utilizied usage of over-designed thickness of steel tubes and thickness of the composite material, to allow the debonding failure to exhibit and to be studied in terms of size-effects and multi-axial behaviour. Optimizing of the composite design and realizing thinner composite material will be used in real deployment of wrapped composite joints which is part of the scope of investigation in the WrapNode-II project (2023-2026).

8. Conclusions

Wrapped composite joint is a breakthrough tutilizing bonding and fatigue resistant composite material to connect steel tubular members instead of welding. The main advantage is that the superior fatigue life of wrapped composite joints leads to a more economical design of the jacket as significant steel quantities can be reduced.. To verify this, full-scale fatigue test on one X-joint resembling joint in wind turbine jacket support structure was tested in Cronos testing rig at OCAS laboratory in Belgium. The tested wrapped composite joint connects steel tubes (ø601x25 mm) without any welding. Damage equivalent load on the joint in jacket structure corresponding to 25 year operation of 14MW turbine was applied within 1 million cycles. In addition, tripled damage equivalent load was applied with aim to impose damage and characterize failure life of the joint. Following conclusions and key findings are drawn:

- The composite joint results demonstrate that it outperforms a similar welded connection with a factor 5000. No damage was observed in the joint after 1 million cycles at damage equivalent load level (+/- 250 kNm our-of-plane bending) corresponding to 25 year operation of 14MW turbine. A welded joint with same diameter and thickness of steel tubes would have consumed its lifetime.
- When the cyclic load level is tripled, which roughly corresponds to ULS load levelthe wrapped composite joint can survive more than 25 years. Joint survived 1.8 million cycles at the tripled, high, load level of +/- 750 kNm resulting in 236 MPa nominal stress range in steel tube. The tests at this level showed that the fatigue life of the wrapped composite joint outperforms by approximately two orders of magnitude (70 times) the fatigue life of equivalent welded joint at full-scale which is expected to fail at 26 thousand cycles due to stress concentration around the welds.
- With these excellent fatigue resistances of the composite joint the use of steel in offshore renewable foundations can be drastically reduced. This initiates a more sustainable use of materials and more economical foundation design. The reduction of foundation weight also requires smaller cost effective installation vessels.
- With the demonstrated extensive lifetime the composite joint in there-use of complete structures or extension of lifetime of structures to 100 years is suddenly a realistic goal.

- Such outstanding fatigue performance of wrapped composite joints demonstrated in the full-scale test opens the path to unprecedented designs and optimization of jacket support structures for offshore wind and the floating support structures that are even more governed by fatigue.

With fatigue issues out of the way for connecting tubular members, the use of high strength steel can be realized and utilized in its strength, and hybrid structures, combining (tubular) members made of other materials with steel, can be realized when wrapped composite joints are used.

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