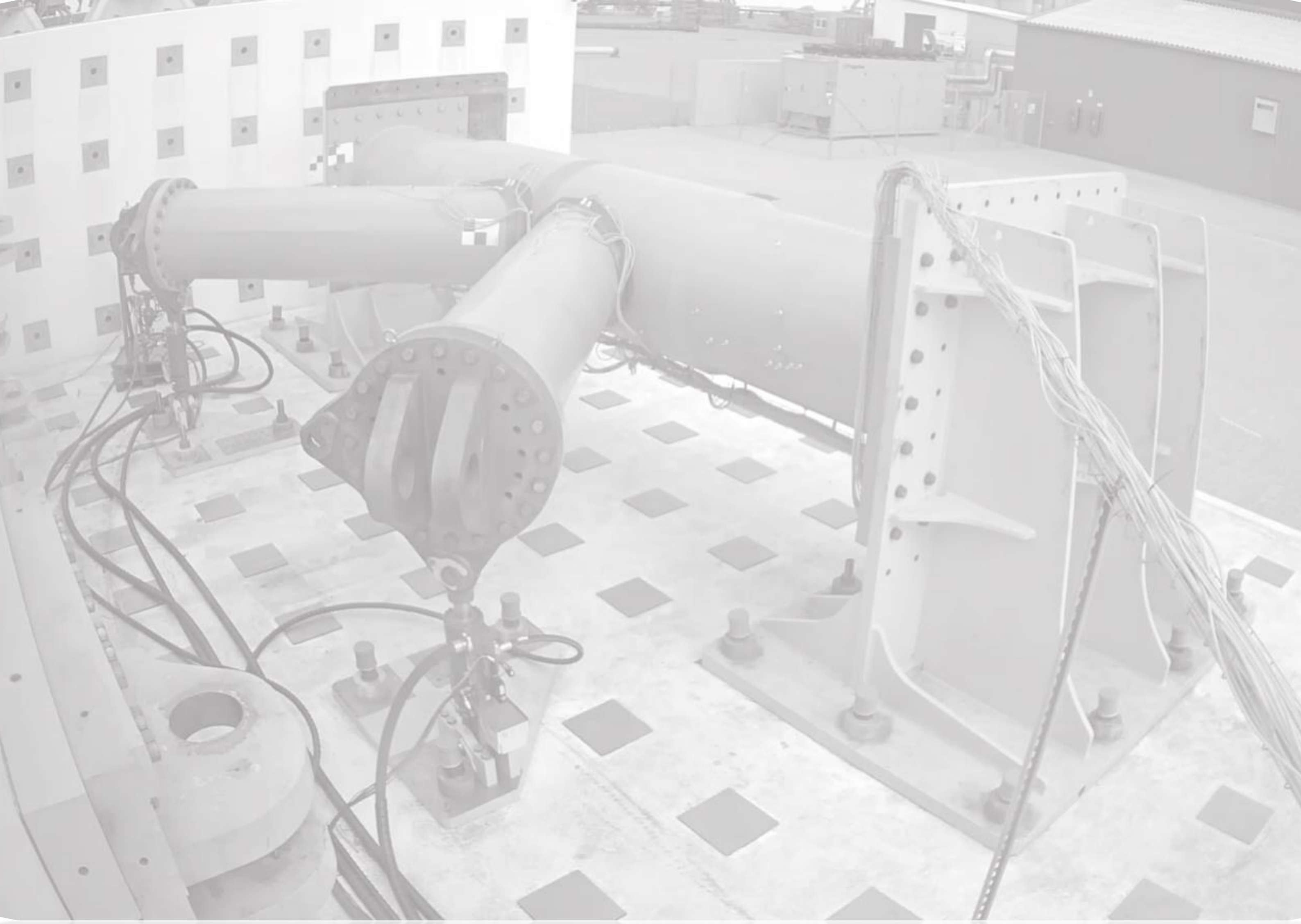

OFFSHORE WIND FOUNDATION NODE ON AN INDUSTRIAL SCALE

FINAL REPORT

EUDP - 64014-0537

Content

1.1 Project details

Project title	Offshore wind foundation node on an industrial scale
Project identification (program abbrev. and file)	64014-0537
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Siemens Gamesa Renewable Energy Borupvej 16, 7330 Brande, Denmark
Project partners	▪ Siemens Gamesa Renewable Energy ▪ Force Technology ▪ Bladt Industries
CVR (central business register)	76486212
Date for submission	2019-01-31

1.2 Short description of project objective and results

English

The project aims to develop a new node for offshore wind foundations. Objectives are: 1) New design for process and assembly of jacket foundations; 2) Cost-efficient welding of nodes; 3) Mass-production process of nodes; 4) Demonstration and test of corrosion, load and fatigue of nodes.

Project results showed that

- Laser hybrid welding is a promising technology to produce nodes and that this process will reduce the welding time by a factor 30 to approx. 15 minutes per brace.
- Automatic robot welding of nodes is not possible at present and that no companies can supply nodes with this type of production yet.
- When using automatic welding, the payback period for the investment of the production facilities will be between 1 and 3.6 years, and that a saving of up to 30% over a 5-year period can be achieved.
- There is an immediate difference in the durability of the welds based on the production method.
- Based on new S-N curves, the thickness of the steel can be reduced by 14%.
- Most of the tested paint systems performed well, but that a zinc-rich primer would reduce the rust creep.

Danish

Projektets formål er at udvikle en ny knudesamling til offshore vind fundamenter. Der udvikles 1) et nyt design for proces og samling af jacket fundamenter; 2) omkostningseffektiv knudesvejsning; 3) masseproduktionsproces. Derudover vil der være test og demonstration af korrosion og holdbarhed af knudesamlingerne.

Projekts resultater viste at

- laserhybridsvejsning er en lovende teknologi for produktion af knuder og at denne proces vil reducere svejsetiden med en faktor 30 til ca. 15 minutter pr. samling.
- Automatisk robotsvejsning af knuder ikke er muligt på nuværende tidspunkt og at ingen virksomheder kan levere knuder med denne produktionstype
- Ved brug af automatisk svejsning, vil tilbagebetalingstiden for investering af produktionsanlægget være mellem 1 og 3,6 år of at der vil kunne opnås en besparelse på op mod 30% over en 5-årig periode
- Der er en umiddelbar forskel på holdbarheden af svejsningerne baseret på produktionsmetoden
- Baseret på nye S-N-kurver, kan tykkelsen på stålet kan reduceres med 14%.
- De størstedelen af de testede malingsystemer klarede sig godt, men at en zink-rig grunder vil reducere krybningen af rust.

1.3 Executive summary

Regarding welding technology, it has been demonstrated that LHW is a feasible technology for welding larger steel thicknesses related to node joining. It has been demonstrated that welding procedures based on 2-3 passes creates a fully welded joint and that the total weld time is in the region of 15 minutes. For the industries involved new perspectives for joining large steel constructions as nodes more productively, have aroused. If the technology is quickly transferred to the Danish industry, the gain in economy, market share and employment may benefit remarkably. It is now only a matter of when the LHW technology will be utilized. Also, other application within the heavy structure industry may gain from the project results.

Regarding manufacturing of the node, it was not possible to produce a full-scale, automatically welded note in the project, despite great effort. However, several companies were examined for the feasibility of future robot welding. Furthermore, several calculations on the robot welding business case were performed. For the robot welding of the nodes, the initial invest is high, but manpower can be reduced radically. Under optimal conditions, the investing in the robot will have a payback period of 1 year and for not optimal conditions, the payback period will be 3,6 years. Further investigation of the business case showed that changing the production method from manual to automatic will result in a saving of up to 30% over a 5-year period.

Three full-scale K-node structures were manufactured, and fatigue tested at LCST at Lindø. The three nodes were manufactured with only small overall geometric differences and were tested in out-of-plane

bending or axial+in-plane bending, which targeted different locations around the welded joint in fatigue. Two nodes were made with semi-automatic welding techniques and the last node was made with fully manual welding. The results from the fatigue tests consisted of hot-spot strain measurements, cycles to crack initiation and through thickness cracks and crack locations. The results indicated that the first node loaded with axial and in-plane bending, cracked prematurely, wherefore it for the S-N curve generations were excluded as a data point. The fatigue life from the second Axial+IPB node was also much higher than the for the first node, also indicating some premature failure in the first node.

The comparison between the new S-N curves and the second Axial+IPB node, which was manually welded, showed good consistency. This could, to some point, indicate that the actual increase in S-N curve is not due to the OPB nodes being semi-automatically welded, but perhaps that the overall welding techniques and methods are improved compared to when the first S-N curves were developed.

Applying the newly generated S-N curves to a base case of the DTU 10 MW jacket, showed an improvement in fatigue life of 900 years or reduction in chord thickness of 14 percent, when utilizing the new S-N curve.

The aim of coating system assessment was to compare conventional coating systems based on wet paint technology with fusion bonded epoxy technology with special attention to the application in offshore environment. In general, no cracks were observed on any system in the thermal cycling test except the glass flake systems and the wet epoxy and the FBE systems showed expected flexibility of about 2 %. All systems pass the immersion test showing no blistering and no rust, and the rust creep from the scribe is well below 8 mm. In ageing testing approximately, half of the systems pass the ISO 20340 requirements. There is a strong indication, that zinc primer improves rust creep resistance

The study, production and testing of the node was an important step towards driving down costs for jacket foundations, thereby reducing the price of wind energy. The project was primarily initiated on the initiative of Siemens Gamesa's plans to develop their concept for jacket foundations and make the technology more competitive. Developments have already required enormous amounts of R&D and testing of the node was one of the last steps before Siemens Gamesa, together with a number of other partners, could take the big step and test and demonstrate a full-scale concept with modular suction buckets, modular jackets, new transition piece of concrete, new cable connection and a new, large wind turbine in an extensive H2020 project.

Several of the project's results are already being used in another project, CeJacket, which is about developing more efficient methods of producing jackets. The goal is also to reduce the cost of jackets. In addition, the results from the node project are transferred to i4Offshore.

1.4 Project objectives

The project was organized with four work packages distributed among the project partners: WP 1 (Design), WP 2 (Welding), WP 3 (Manufacturing) and WP 4 (Demonstration). Each WP had several, well-defined activities and milestones, as listed below:

WP		Activities	Milestones
WP1z (SGRE)	Design	▪ Incorporation of results from work packages 2-4 into the design. ▪ Optimize the node design for manufacturing. This includes any potential update on restrictions on bracing angles, limits on material thicknesses or reductions on the length of the stubs. ▪ Maintaining overall cost picture and monitor cost reductions per value chain element. ▪ Get benchmark figures for the node production from suppliers outside Europe. ▪ Ensuring that the right designs and decisions are made in the individual WP.	M1: Updated design basis for the node taking requirements from manufacturing methods into account. M2: Updated design of the node inclusive all potential implications to the overall foundation design and other value chain elements.

WP2 (FORCE)	Welding	▪ Laser hybrid welding procedures will be developed for the selected node material and the materials to which the nodes are to be joined. ▪ Equipment, materials, geometry and welding process will be evaluated/optimized. ▪ Standardization and certification of welding processes include testing, review of existing laser hybrid welding standards and collaboration with classification societies. ▪ Process to take the flat coupon welding to the actual node geometry. ▪ Generation of testing data and evaluation.	M3: Node weld geometries defined M4: Welding procedures (WPS) for selected materials and thicknesses performed. M5: Weld procedures incorporated with selected node geometries.
WP3 (Bladt)	Manufacturing	▪ Screen potential automated welding methods for their feasibility for automated node production. ▪ Compare cost and investment for laser-hybrid welding process and/or other feasible automated welding solutions. ▪ Verify quality and productivity through tests. ▪ Develop virtual industrialized production line layout.	M6: Select most promising option(s) for in-depth analysis. M7: Go / no-go decision for testing at scale after evaluation of cost, investments and quality. M8: Completed scale tests and final evaluation. M9: Layout of industrialized production setup.
WP4 (FORCE)	Demonstration	▪ Accelerated high frequency tests on full-scale nodes demonstrating min 25 years of service life. ▪ Assembly of selected modules to examine the risk of damages in coating and weldings. ▪ Develop and demonstrate procedures for quality control. ▪ Corrosion control options will be defined.	M10: Fatigue data simulating min 25 years of service life is generated. M11: Effects of damages are highlighted and understood. M12: Quality control procedures are described. M13: Corrosion control and monitoring concept developed.

Already on an early stage in the project, calculations, specifications and drawings for manufacturing of the first node was completed. In the first stages, a procedure for laser hybrid welding was produced and a suitable supplier was identified. However, the automatic welding facilities at the supplier was not compatible with a structure as heavy as the node and adjustments were made. This resulted in an only partly automatically welded node. The same situation applied for the second node despite great effort to deliver a fully automatically welded node. Also, the laser hybrid welding was deemed not suitable due to fatigue problems. This resulted in two semi-automatic welded node and one fully manual welded node.

Due to the problems with the laser hybrid welding, corresponding more time was spent on the corrosion testing. In this activity, FORCE had the lead and performed the analysis of the test subjects. At this stage, the interest in the project from the industry was quite high and the coating system assessment was extended with help from Hempel and Jakob Albertsen, who provided the paint and test plates for the corrosion test. The coating system assessment was completed on time and with great results.

In the fatigue test, FORCE's test bench at LORC was used to test the full-scale nodes. At this point, that project was prolonged with six months due to the challenges with the automatic welding of the nodes. During the test of the first node, there was a malfunction on the test bench at FORCE and cylinders broke. Challenges with finding new, durable cylinders led to another prolongation of the project in this crucial phase of the full-scale test. In the meantime, the node was changed with the second node for only axial bending test to save time. Test of the last node was completed according to the test plan.

Test of the two nodes were following by test of an additional node, provided by Ørsted. This was a chance to combine a different production method with the already existing data from the two previous nodes and make a complete data analysis. This resulted in a last six-month prolongation of the project, but also generation of much more data, adjustment of the test and added value for more than DKK 4 mill.

In the analysis of the data, the project received further added value from Rambøll, who provided most of the test analysis. The analysis was carried out by an industrial PhD student in cooperation with FORCE. Additional data analysis was performed by a research assistant at Aalborg University, regarding FEM calculations on the crack formation.

In total, the project received extensive added value from industry throughout the period despite the total prolongation of two years.

1.5 Project results and dissemination of results

WP1 – DESIGN

To speed up production rates of jackets, multiple jacket fabricators are looking into automating the complex weld between chord and bracings (the nodes). The chord section at the node and 2 to 4 brace stubs are welded in a separate welding station, consisting of a manipulator (holding the node) and a robot arm with welding equipment. Joints to the other jacket elements are easier and can be made with for instance orbital welding. The connection is welded with a robot welder with manipulator. Scanning of the weld seam and fill welding is all performed automatically. Fit up will be partially automated and root layer will be welded manually.

Automatically welded nodes are expected to have better weld qualities compared to conventional point-to-point brace to chord connections, because of more consistent welding quality through automation and because welding is in horizontal (1G) position (compared to partially overhead 6G/5G position for point-to-point construction). Additionally, it is possible to weld from the inside, improving the fatigue performance on both sides. Note that this depends on the size of the brace stubs: for small stub sizes it will be difficult to make a root pass from the inside. Furthermore, weld seam preparation and fit-up can be automated, resulting in improved control over the weld gap.

Because of the improved weld quality, it can be expected that fatigue performance will also increase. Studies performed by Ramboll on the Siemens Gamesa gravity jacket have shown that design drivers for the node weld are chord thicknesses and brace stub diameters. Hence, potential savings are in this area. Current chord thickness levels (>60mm) are more difficult to roll at typical diameters (1-1.5m). Reducing brace diameter would save a significant amount of steel. Potential weight saving on the jacket with improved fatigue performance (from DNV D-curve to C1-curve) is in the range of 10-20%.

SAZG/BMO is proposing to consider two deviations from conventional node brace welding as described in the DNV and GL guidelines, to improve production rate and weldability. The first is to use GL Rules for Classification and Construction 2007, IV Industrial Services, 6 Offshore Technology. Note that this detail is not in GL Rules for Offshore Wind turbines 2012. However here the root pass will be made from the inside. Also, DNV-GL is asked if this can be extended to brace angles of 45deg. Note that this looks like AWS weld details. The detail described in the GL2012 code is difficult to produce with standard weld torch due to small bevel angle and opening. This would mean changing of the weld torch for this small region, which would not be changing to the proposed weld detail would facilitate the production process.

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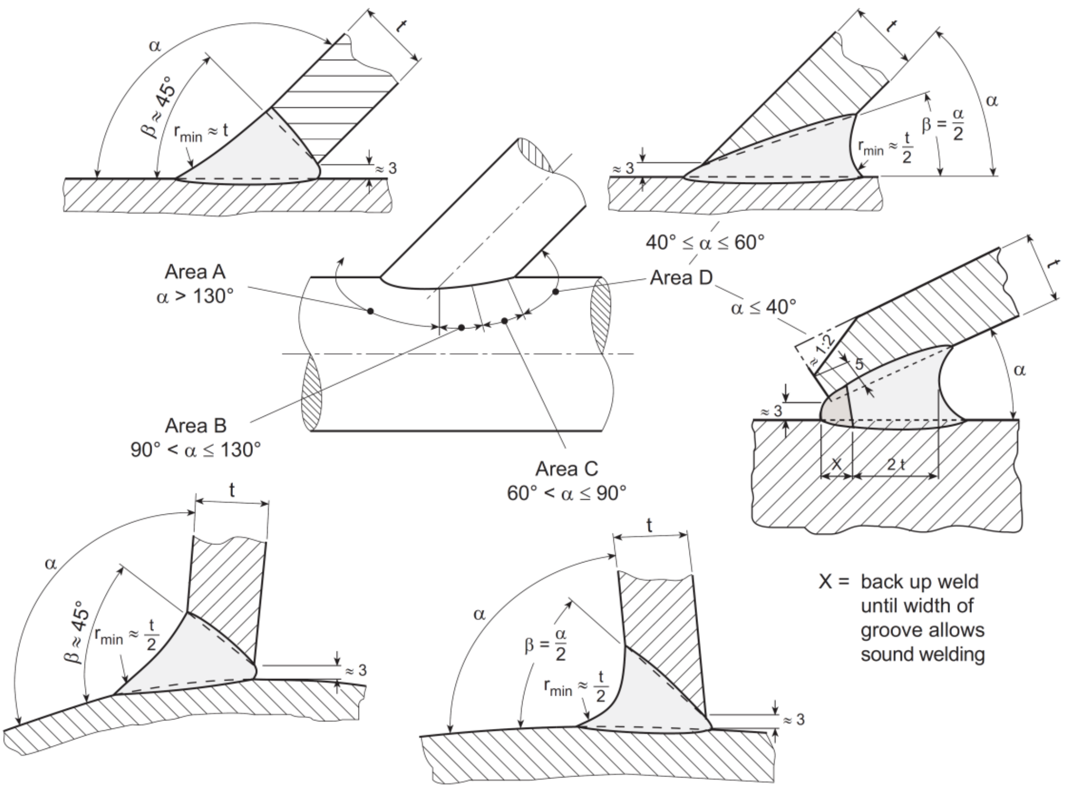


Fig. 4.15 Typical tubular weld connections without back welding

Figure 1: Excerpt of GL with weld detail for crown heel points at lower brace angle.

The second proposal is to use an oscillating weld torch instead of stringer bead welding.
Benefits are

- Easier to adopt seam preparation variations, for instance due to ovalized tubes.
- Higher deposit rates and improved control over the weld toe geometry. This will imply a smoother transition at the weld toe. Downside possible reduction in fracture toughness (due to increased heat input) of the weld and hot cracking (probably not an issue for the small oscillation width).

Oscillation range is around 4mm the wire diameter (typically 1.2mm or 1.0mm), which is slightly higher than directly allowed by DNV-GL (3times wire diameter). In a first comment DNV-GL has stated that it should be possible to accept. SAZG have proposed to do some Charpy tests on some mock-ups with oscillation. Hence, it can be useful to apply this technique.

Previous fatigue tests of nodes

Many of the codes (DNV, API, etc.) prescribe fatigue curves for tubular joints. The curves are a large part of the fatigue of nodes done in the 70's and 80's. Many of the tests were performed with smaller chord thicknesses (15-30mm), which are smaller size than typical nodes for WTG jacket foundations. Below is a listing of the fatigue tests on nodes done in the past (based on literature).

As can be seen, the number of tests performed on nodes with thicker chords is very limited. Furthermore, no tests were performed on out-of-plane bending loading. The tests as described in this document would therefore significantly increase the knowledge on full-scale nodes.

Chord wall thickness	Total number	Axial loading	IPB	OPB
16-19mm	59	21	9	29
20-32mm	21	16	5	0
40-50mm	6	2	4	0
70-80mm	7	6	1	0
total	**93**	**45**	**23**	**29**

Table 1: Number of fatigue test specimens on nodes (based on literature, source OCAS). (IPB = In-plane bending, OPB = out-of-plane bending).

Test goals

Purpose of the tests is to:

1. Get better insight in the fatigue performance of Automatically Welded Nodes
2. Test effects of modifications to the weld detail and process
3. Get insight in crack propagation (speed)
4. Calibrate FEM models to strain measurements
5. Check if full FE analysis of the real weld geometry (measured with 3D scanning) and loads, to see if this can predict fatigue life (this is outcome of SLIC project).
6. Ultimately the best outcome would be a dedicated s-N curve for Automatically Welded Nodes, or a justification to use a higher s-N curve (C2 or C1 curve) for these welds. This would then need to be approved by certifying authorities like DNV-GL.

If the welds perform better than the DNV approved T-curve for nodal joints, then ideally the outcome of the tests would be a dedicated S-N curve for Automatically Welded Nodes, or a justification to use a higher S-N curve (C2 or C1 curve) for these joints. DNV-GL requires that the mean curve is estimated with at least a 75% confidence from the tests.

Amongst others, Ørsted is interested to test findings from the SLIC project (monopiles), that showed that fatigue life can be accurately estimated by doing FE analysis on the actual weld (toe) geometry. This can be obtained with full 3D scanning of the weld. The SLIC project focused on monopile welds, and Ørsted would like to test if this theory also holds for K-nodes.

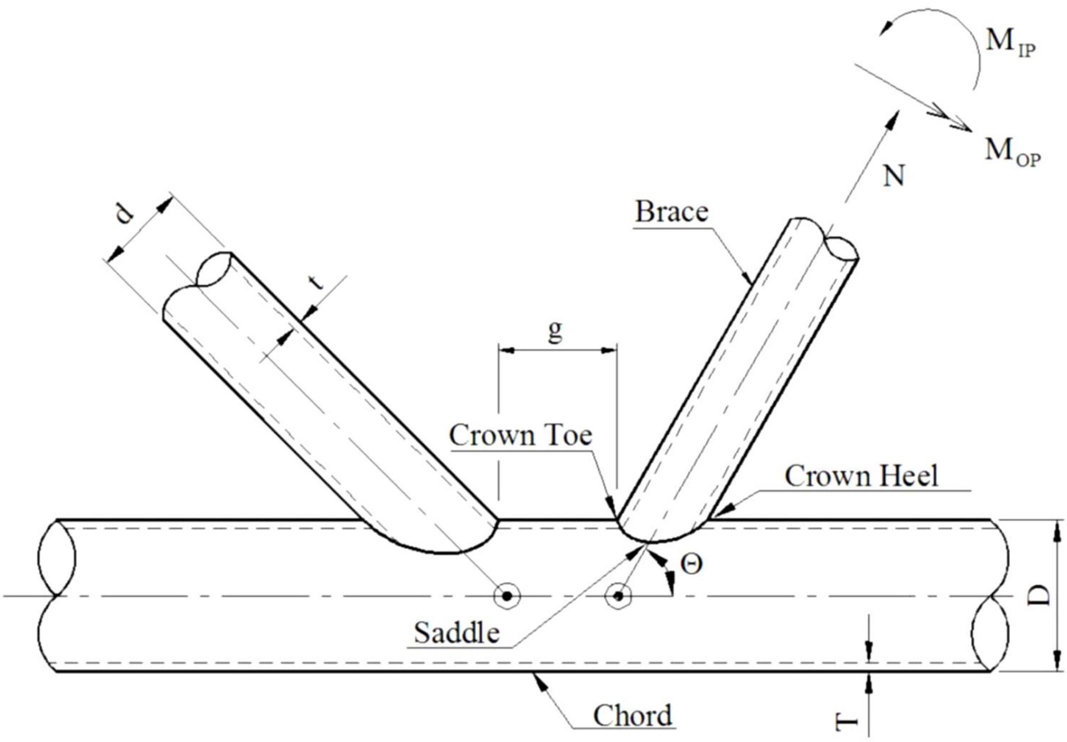


Figure 2: Geometrical definition of K-node.

WP2 – WELDING

Laser-hybrid welding (LHW) is a novel process combining arc-welding and laser welding in the same process taking advantage of both technologies. Chief benefits are improved tolerances to joint fit-up, improved weld quality, increased single pass penetration depth, increased welding speed and lower distortions. Further, high-power laser-hybrid welding has the potential to develop and optimize the manufacturing logistics. High power laser-hybrid welding in thick sections – such as in heavy off-shore structures – is still in its infancy. Nowhere is there any experience in thick section laser-hybrid welding in sections of 25-60mm and beyond, and the literature on the topic is limited.

FORCE has invested in one of the world´s most power-full laser-hybrid systems available in private industry for R&D-collaboration, industry projects and contractual work – a fully robotized 32kW disk laser system. The initial work done by FORCE has already showed a vast potential for an order of magnitude gain in productivity. The development of a cost-efficient automated laser welding process for the nodes has the potential to eliminate one of the main challenges for the jacket foundation type. The laser welding technology is still in its infancy and the work of integrating this new technology into the concrete development of the modular foundation will be progress beyond state-of-the-art.
The work package WP2 therefore aims at developing the laser-hybrid welding technology as the innovative technology to be implemented in a node production line.

The project objectives are described shortly as

- Optimizing NODE geometries for LHW
- LHW process development
- Demonstration of the LHW process to be a cost-efficient joining method for NODE's.

The related milestones are

- M3: Node weld geometries defined
- M4: Welding procedures (WPS) for selected materials and thicknesses performed.
- M5: Weld procedures incorporated with selected node geometries.

The optimization of weld geometries was performed in steel quality S355J2 in thicknesses 22-40 mm. Mainly I-butt and T-joints were investigated as basis for the NODE-joint geometry. Approved welding procedures WPS and WPQR were obtained.

To demonstrate the feasibility for LHW related to the NODE geometry (brace mounted at 40 degree), already approved welding procedures were utilized at geometries simulating the four main positions at the saddle curve connection. The NODE connection varies in thickness along the saddle curve in the range 22-34 mm. It was demonstrated that it was possible to perform the total LHW weld in 2-3 weld passes in all the four main positions based on the use of approved welding procedures.

It was demonstrated that the total weld time for LHW of one brace is about 15 minutes. This is more than a factor 30 improvement in productivity compared to to-days manual welding of the nodes.

This means that all the mentioned objectives and related milestones related to the LHW technology were fulfilled during the WP2 activities.

The results clearly make the LHW technology very interesting for future production of NODES. The demonstrated increased productivity have created very promising perspectives for the technology.

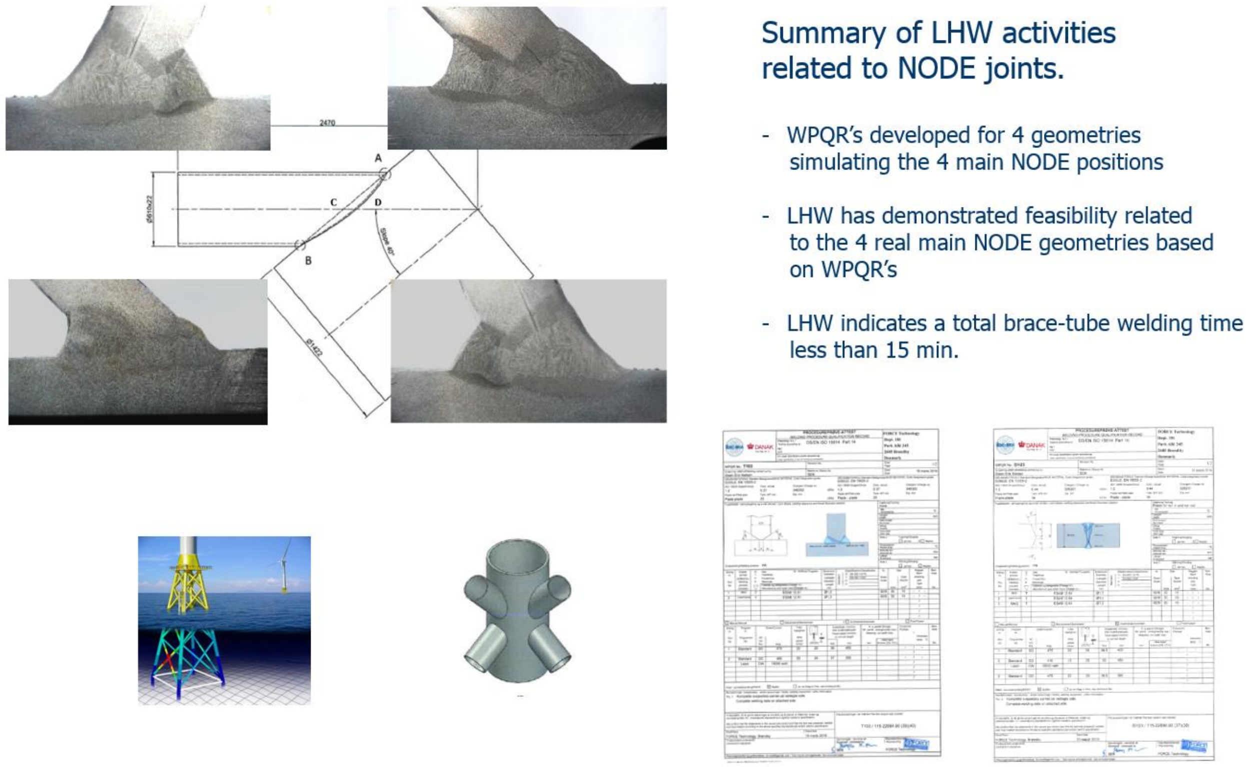


Figure 3 LHW of a Node was demonstrated for the joint geometry in the four main connection positions based on approved welding procedures developed during the project.

The project has been presented at the following fora:

- Technical magazine: SVEJSNING – February 2016. 'Offshore konstruktioner til vindenergi og højeffektiv lasersvejsning.' by Steen Erik Nielsen, FORCE Technology.

- TUFW conference – Hamburg, May 2016.' High power laser hybrid welding – challenges and perspectives for the windmill manufacturing industry.' by Steen Erik Nielsen, FORCE Technology.

WP3 – MANUFACTURING

Feasibility for automated node production

The choice of welding method has been an iterative process, chosen in close cooperation with the supplier of the robotic solution. Different welding methods have been considered. Finally process 138-flux cored welding wire - metallic powder type has been chosen. The welding position is down hand PA.

The wire used for the testing is NSSW SM-47 A - Data sheet enclosure 2.
This is chosen because is quite effective and has a good penetration- and has a thin slag.

Other methods could possibly be used in the same setup in give a higher deposition rate e.g. process 121 submerged arc welding (SAW) or process 138 with twin arc.

For a start, it has been focused on controlling the process instead of looking so much to maximize the deposit. The automated welding is only used for the filling and cap layer - the root is welded by manual welding using the same WPS that are used for the Wikinger project at Lindø - WPS 140-447 rev 1 - Enclosure 3.

During the project period several suppliers have been contacted to find a relevant partner for cooperation:

Migatronic Automation

Migatronic is quite far with automation and robotic solutions. It is our opinion that they typically work with smaller items that we need and that their sensors for scanning complex weld groves are not on sufficiently high level

Valk Welding

Valk Welding is a Dutch company with a department in Denmark. We have had a contact to the company. Apparently, there are quite far inside the area, but they have a cooperation agreement with a Dutch contractor, which means that they cannot cooperate with others before earliest in 2 years (2017)

IGM

IGM is an Austrian company with a department in Sweden. We have had a good deal of contact with the company. They are quite far inside the area, for instance they had an animation of a robotic station welding nodes on the wind exhibition in Bellacenter in spring 2015. They have made a strategic cooperation agreement with Bilfinger and Salzgitter, which means that they cannot cooperate with other befare earliest in 2 years (2017)

It is told that Bilfinger-Mash in Poland have orders same robotic stations by IGM. Obviously, they work after same concept as we do - that is manipulating the node itself and weld downhand using flux cored wire - they are uing twin arc and get a quite high deposit rate.They say that they also weld the root by robot - both inside and outside

lnrotech

lnrotech is a small Funen company, who works with smaller robotic solutions. They have made a robot, which have welded TP-st oppers on site on the North Sea.
The contact with lnrotech came a little late in this node project, and we had already chosen our partner for this project. It is an innovative company, that also works with scanning with sensor in connection with the robotic welding. It is our impression that they believe that are on a higher level than they are in praxis.

PEMA

PEMA is a Finnish company, which solely works with automation of welding. It turned out that they were quite far with mastering scanning with sensors of welding in thicker materials with varying geometries. They have approximately 150 employees and we ended up choosing them as partners for the project

Bladt Industries have visited them a couple of times during the project and it is our impression that they supply quality equipment in the expensive segment - and they do a great effort to supply solution that works and are easy to use.

Method statement — manual contra automatic welding

<u>Assumptions:</u>

- Braces to be welded from 2 sides. if this is not the requirement the advantage to produce loose nodes will be less favorable, because extra weld in the bracings will be introduced.
- Two calculations are made (see below)— the optimal where the design is with double side welding - and where only single side welding is required and therefore an extra weld is introduced to the bracing.
- The fit-up of the node and the welding of the root pass to done manually for both processes.
- We estimate that 72 node-brace weldings can be made automatic each jacket instead of manually.
- We estimate that 24 SAW welding must be done after node welding- extra work estimated 3 hours pr. weld.
- We calculate on 50 jacket pr. year—that is 3600 node-brace welding each year.
- We assume that it takes 37 hour (tIND0)— for manual welding and 8,0* for automatic welding.
- Half of the saving going from manual to automatic welding is achieved from the more deposit rate itself, using high current in the optimal position PA. The rest is coming from the better uptime.
- The repair rate for manual welding 2% - for automatic welding 1% - price pr. repair DKK 10.000.
- The calculation is on an average node" — ø838 x 25 — angel 45 -(weld length of ellipse: 3424 mm)

* This number is based on Bladt own estimations made during our welding at PEMA 17-18 November 2015. This is probably quite conservative- The PEMA report estimates this to be approximate, 4 hours)

Manual welding

Pros	▪ Legs can be delivered from subcontractor in longer pieces- with some of the circular welds finished
Cons	▪ Many skilled welders to be used. ▪ We assume that the circular seams that must be made at Bladt is a little more expansive than ones bought from subcontractor (+ 3 hours work time included in calculation). ▪ The quality of the weld will depend on the welder— and to some extend on the weld position.

Robot Welding

The leg piece (chord) of the node to be delivered loose.

Pros	▪ Many weld hours can be moved from erecting to prefabrication. ▪ The quality of the weld will be uniform and on a high level. ▪ A fixture can be made for each type of node- to get good assembly tolerances.
Cons	▪ Circular welds in the leg to be welded after the node is finished —the turning of the leg require more expensive equipment as the weight of the leg is eccentric.

Pricing DKK- Optimal —Design with double side welding — no extra welding in brace

	Manual Welding DK	Automatic Welding DKK
Equipment- price	1,250,000	41,000,000
100% repairs pr. year	72 welds	36 welds
Price repairs pr. year	720,000	360,000
Equipment pr. year maintenance	62,500	1,950,000
Welding hours	133,200	28,800
Hourly rate	400	400
Price manpower	53,280,000	12,960,000
Sum ex. depreciation	54,062,500	14,910,000
Payback time: 1,05 years or 12,4 months.		

Pricing DK- Not Optimal — Design with single side welding -1 extra welding in brace

	Manual Welding DK	Automatic Welding DKK	Remarks
Equipment- price	1,250,000	41,000,000	
100% repairs pr. year	72 welds	36 welds	
Price repairs pr. year	100,000	360,000	
Equipment pr. year maintenance	62,500	1,950,000	
Welding hours	133,200	28,800	
Extra weld in bracing	0	68,400	19 hours pr. weld (3600 welds)
Hourly rate	400	400	
Price manpower	53,280,000	40,320,000	
Sum ex. depreciation	54,062,500	42,630,000	
Payback time: 3,6 years or 43,2 months.			

Estimation of total reduction of price for both scenarios.

We estimate that the Interest rate is 6% and the depreciation for equipment is 5 years.
The cost pr. kilo for the manual welded node is estimated to EUR 3 pr. kilo inclusive material. Material part EUR 1.7. Work/handling: EUR 1.3.

	Automatic welding Optimal scenario	Automatic welding Not optimal scenario	Remarks
Saving 5 years production (DKK)	195,762,500	57,162,500	
Decrepitation of equipment (DKK)	41,000,000	41,000,000	
Interest Rent (5 years) – 6% (DKK)	12,300,000		
Savings (DKK)	142,462,500	3,862,500	
Savings pr. node (DKK)	28,992	772,5	1000 nodes pr. year
Savings % - if node is estimated 10 T. Compared to total cost	12,7%	0,3%	
Savings % - if node is estimated 10 T. Compared to total work/handling	29,7%	0,8%	

Decision for testing at scale

Bladt Industries entered the project in hope to get solutions on how to reduce total welding time on the production of jackets, especially with focus on welding of the Y-nodes between braces and legs. As this joint to their knowledge has only been welded by use of manual welding methods so far, they were aware of the complexity of the task, but also with expectation that it can be possible to utilize mechanical or robotic solution and through this to obtain a both quality and economic benefit.

Contacts were made to providers of welding equipment and robot companies and manufacturers of equipment for manipulation of nodes. Some of the critical issues are the variation in joint preparation around the node, accuracy/tolerances in production, welding positions involved, access for the welding gun in the heel of the joint, root pass welding, programming of the manipulator/welding gun, and finding the right welding process for these different conditions.

Soon it was discovered that laser welding is the future with fast welding speed and other benefits, but currently also limited to e.g. production tolerances and the change in the weld joint around the node. It was more likely to become a success if the manual welding process was being transferred to a semi-automated/automated/robotic solution. When taking this last decision, Bladt Industries were also able to deliver a suitable node to the other WP of this project.

Completed scale test

Bladt Industries entered in contact with PEMA who had a solution to manipulate the node. The root pass was welded manually at BI since there are no existing solutions to do this on a robot. Yet. Once prepared, the test pieces were programmed on a robot and test welded with arc welding. It required 6 test pieces to get to a reasonable suitable node which could be used for the other WP.

Further optimization of the program and the weld sequence would be necessary, but the first results gave an indication that this is possible. Welding time of a robotic welded node compared to a manually welded node was approximately half. In this project it was the target to weld a node as a component. By this a robotic solution using a manipulator was chosen. However, this solution is not suitable if the brace pipe is welded onto the leg as a site weld.

The cost for a site welding solution will be lower as there is no need for an expensive manipulator for test components up to 20 tons of weight. However, the solution for site welds in any position, including uphill and overhead, and in both ground level and in heights will require a special set-up which has to be invented and which could be costly also.

Layout of industrialization production set-up

There are basically 3 types of nodes.

1. Welded as a component which is as per this project. Welded either single or both sided. The node can be manipulated, meaning that the weld can be in the flat position and leading to the highest deposition rate (kg/h). A flexible production set-up which means that the node can be manufactured almost anywhere if the equipment is suitable for this. However, the equipment is rather stationary as it weights many tons and must be bolted to the floor.

2. Site welded as a short brace on the leg, allowing both welding single or both sided. This means welding in position with adjusted welding parameters (less deposition rate compared to A). Flexible solution which can be shipped to the actual work site. No need for expensive and inflexible manipulator but requires a flexible site set-up (fixture) for position welding.

3. Site welded as a X-brace on the leg, allowing only welding single sided. This means welding in position with adjusted welding parameters (less deposition rate compared to A). Flexible solution which can be shipped to the actual work site. No need for expensive and inflexible manipulator but requires a flexible site set-up (fixture) for position welding.

The solution used in this project is for type A only. A solution for B and C will also be able to be used for A without the need of a manipulator. Only difference is that instead of manipulating the welded piece to the right position, it is the welding gun that is being manipulated to different positions.

Choosing type A or B will require more position welding on other butt-welded seams around the node. This must be taken into consideration when deciding which production layout to use.

Based on the above thoughts, Bladt Industries has decided to invest in a flexible robot which can be used for all 3 types of nodes. Since the robot doesn´t exist on the marked, the investment contains a developing project as well. Once developed and implemented, Bladt Industries will be the first company in the world to weld nodes in position by use of robot.

WP4 – DEMONSTRATION

Fatigue test description

The test program is split up in 2 different types of tests: 3 full-scale K-node fatigue tests and 15 to 20 small scale fatigue tests on flat specimens that were robotically welded. The full-scale K-nodes resemble node designs typically found in offshore jacket foundations for WTG's.

Small scale fatigue tests

The small-scale tests are used to determine the slope of the fatigue curve. The slope indicates whether the fatigue process is crack initiation or crack propagation dominated. Furthermore, the results can assist to find the target stress level for the full-scale tests (the tests will be performed prior to the full-scale tests).

Small scale fatigue will be tested in constant amplitude tensile tests, performed on a resonance fatigue testing machine at FORCE. As the most likely location for initiation of fatigue cracks it at the weld toe, this is the focus area of these tests. The weld profiles of the small-scale fatigue specimens resemble the weld profile as found in the saddle points of the node.

Tests will be performed on approximately 3 different stress levels, to get good spread of data points on the S/N-curve, and hence get a more accurate prediction of the slope of the S/N curve. The ratio between minimum and maximum stress level is R = (min. stress level)/ (max. stress level) = 0.5 in order simulate better the residual stress that would be present in the full-scale node.

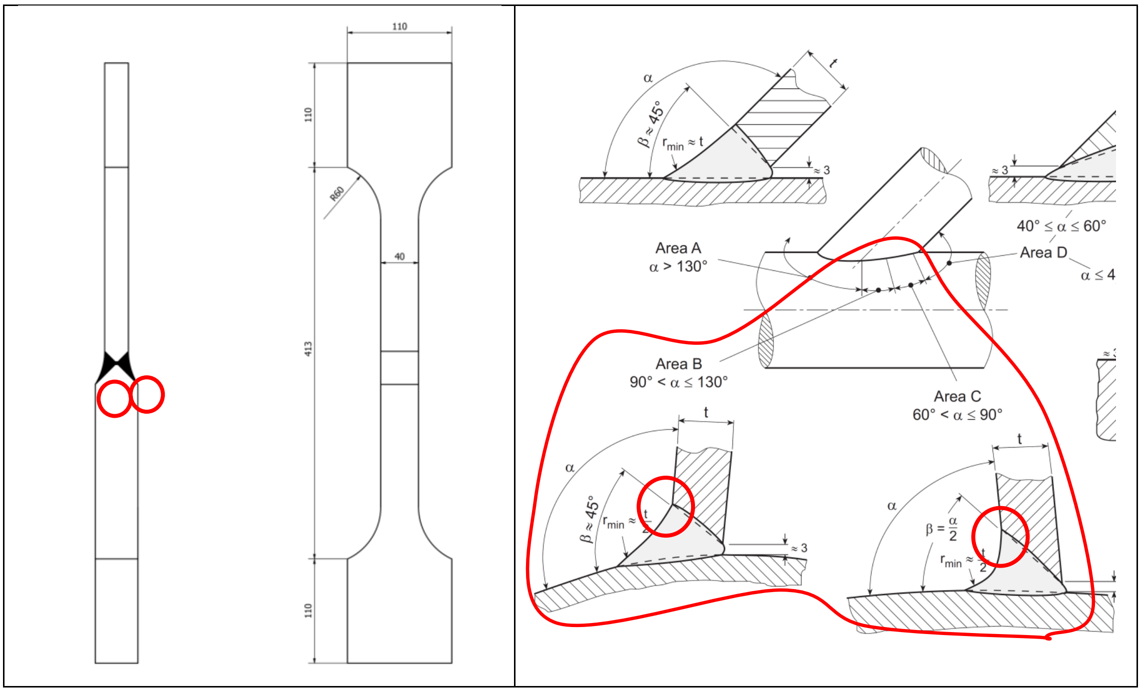


Figure 4: Small scale test specimen (left) and reference to node weld geometry (right).

Full scale fatigue tests

Aim of the full-scale tests is test as close to the real geometry and loads as possible. Hence geometry and production of the node are as close to reality as possible, in this way residual stresses due to welding will be comparable. Furthermore, loading will be like what is encountered in jacket foundations: axial loading, in-plane bending and out-of-plane bending.

Loading of the test nodes

Loading directions will differ between the individual full-scale tests to target different hotspots around the weld circumference (see below and Table 2).

- K-node 1 (Bladt) will be tested in axial (AX) and in plane bending (IPB) direction. It targets hotspots at the toe and heel of the brace weld.
- K-node 2 (BMO/SAZG) will be tested in out-of-plane bending (OPB). This test targets the hotspots at the saddle points of the joint.
- K-node 3 (Bladt) Ørsted wants to target the crown heel points, therefore axial+inplane bending test.

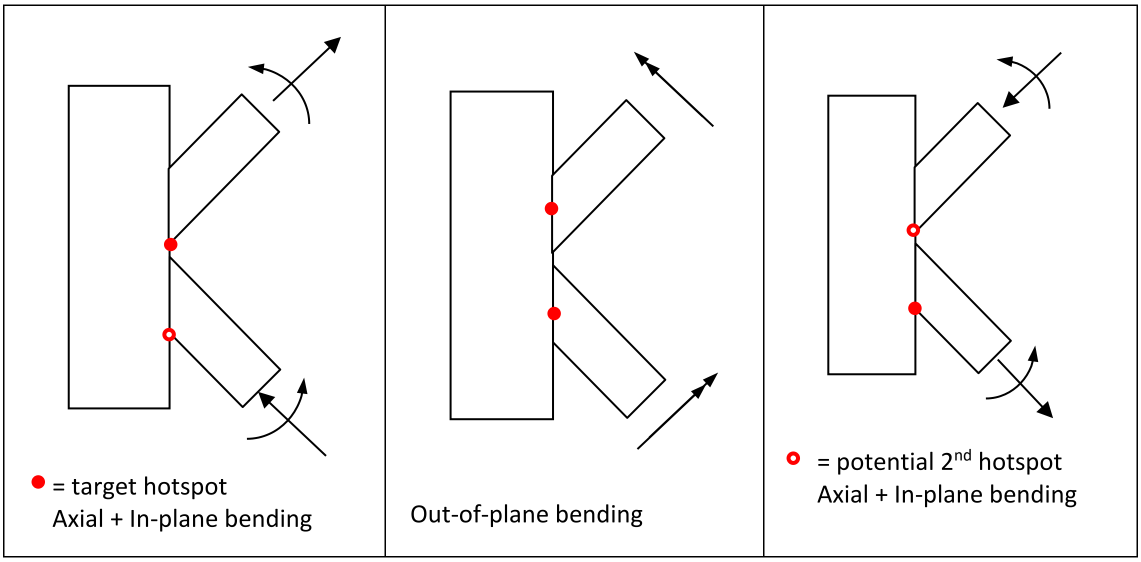


Table 2: Load combinations in test

Tests will run until a complete through crack is detected. In case of the out-of-plane bending test, when a failure is occurred, the test will continue on the other brace stub, to get an indication of the fatigue strength on both stubs.

Stress range in testing

All tests target a fatigue life between 1.0E5 and 2.0E6 cycles, to be far enough from both low cycle fatigue phenomena (plasitc cycling) and a fatigue limit. A fatigue life of 2mln cycles would mean 1month of testing at 1Hz.

Stress levels of around 180-200MPa at the weld toe have a high probability of failure even if the weld performs according to C1 curve. **Fejl! Henvisningskilde ikke fundet.** gives an overview of estimated test times for different fatigue strengths (probability of failure).

The stress ratio R = smin / smax is chosen at R=0.1, to be sure that there is tension –tension fatigue. This state ensures good crack propagation. This will be conservative, as compression-tension fatigue would behave differently, as there is no or little crack growth in the compression part of the stress cycle.

	Cycles to failure							
S/N curve location	T-curve	T-curve + 2st.dev.	T-curve + 3st.dev.	T-curve + 4st.dev.	C1-curve	C1-curve + 2st.dev.	C1-curve 3st.dev.	C1-curve 4st.dev.
Probability of failure	2.3%	50%	86.1%	97.7%	2.3%	50%	86.1%	97.7%
Stress Range								
160MPa	3.6E+05	8.9E+05	1.4E+06	2.2E+06	6.9E+05	1.7E+06	2.7E+06	4.3E+06
170MPa	3.0E+05	7.5E+05	1.2E+06	1.9E+06	5.7E+05	1.4E+06	2.3E+06	3.6E+06
180MPa	2.5E+05	6.3E+05	1.0E+06	1.6E+06	4.8E+05	1.2E+06	1.9E+06	3.0E+06
190MPa	2.1E+05	5.3E+05	8.5E+05	1.3E+06	4.1E+05	1.0E+06	1.6E+06	2.6E+06
200MPa	1.8E+05	4.6E+05	7.3E+05	1.2E+06	3.5E+05	8.8E+05	1.4E+06	2.2E+06
Cycles to failure against stress range, for different failure scenarios. Note: it is at this point unknown how the weld will perform. Therefore, both the standard T curve is included, and the upper bound is thought to be that C1 curve (like grinded welds) is achieved.								

Table 3 Probability of failure for different stress ranges and failure scenarios

Note1: S/N data from DNV-GL-RP-0005 are based on failed (small scale) test specimen. It can be expected that stress redistribution takes place once a crack has formed, which could lead to slower crack propagation. It is an option to do crack propagation analysis in FE. This will be extensive but will give an indication of the rate of crack growth. This can be added to the above table to get a better estimate of maximum required cycles to failure.

Note2: Standard deviation is assumed to follow that as given in DNV-GL-RP-0005. It is however mentioned in the RP that for complex structures scatter (and hence standard deviation??) can be larger.

Typically, the aim in full-scale fatigue tests is to have a fatigue life between 1.0E5 and 2.0E6 cycles, to be far enough from both low cycle fatigue phenomena (plasitc cycling) and a fatigue limit or reduced S/N slope (m=5). From the table it can be seen that for stress ranges between 180-200MPa it is most likely that the test specimen will fail even if weld fatigue performance is very good. In worst case scenario the test will have to be continued for additional 2weeks.

Results of 3D FE analysis of the test K-nodes show that it should be possible to reach these stress ranges with the available cylinder forces.

Test setup description

Test bed

The test is performed at the LORC test facility. This consists of a 3m thick concrete strong floor, and a strong wall of 3m. K-nodes will be fixed to the floor via steel floor adaptors. The hydraulic cylinders are fixed to the strong walls (AX and IPB) and floor (OPB).

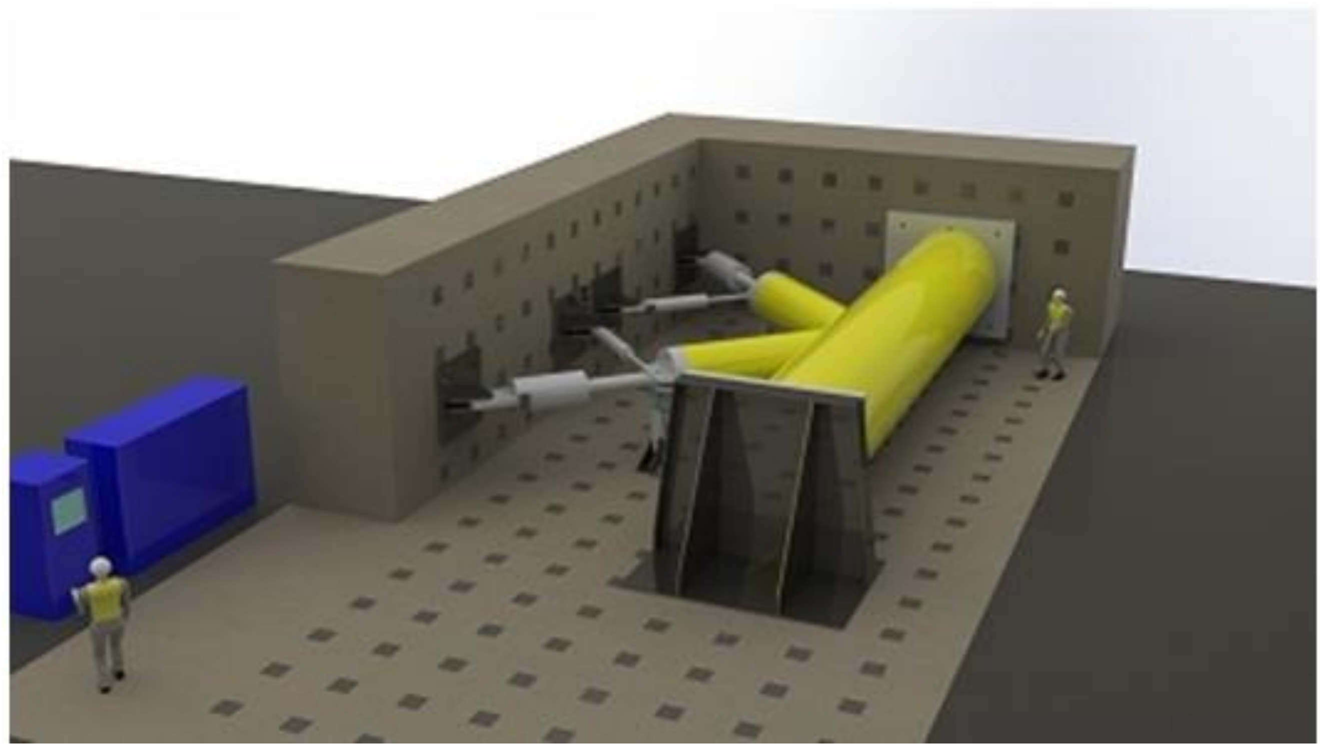


Figure 5: Sketch overview of test setup for K-node on strong floor at FORCE.

Hydraulic cylinders

Loads are applied with hydraulic cylinders. The following cylinders are used:

- Axial cylinder: 1600kN dynamic load (tension)
- In-plane bending (IPB): 350kN dynamic load (tension)
- Out-of-plane bending (OPB): 350kN dynamic load (tension)

Question from DE: how accurate can the loads be applied and in direction, to avoid undesired bending moments? (location of the fixation points of the hydraulic cylinders)

Measurements in test

Small-scale testing results

Actual weld geometry could be determined via 3D scanning of the weld, prior to testing. The hot spot stress in the real weld geometry can then be calculated with FEM to determine point of failure.

For the small-scale testing, it is planned that approximately 15 specimens will be tested at various stress levels generating the corresponding number of cycles to failure and the data points for the S-N line. The data is most conveniently shown in tabular form, as the most important items are the stress range and the number of cycles to failure, N.

Test No.	Target Stress Range, S (MPa)	Number of Cycles, N
01	-	-
02	-	-
...	-	-
n	-	-

Table 4: Small-scale testing results

It is planned to instrument the first 3 test specimens with strain gages to measure the actual strain near the weld toe. The measured strain range results will be used for the correlations between the small-scale testing results and the full-scale testing. The number of cycles, N, are the number of cycles to failure where the specimen is cracked through and is in 2 pieces. From the testing data, the mean S-N curve and design

S-N curves can be calculated. If it is requested these calculations may be conducted and reported by FORCE.

Full-scale fatigue testing

Prior to testing all welds should be NDT according to standard offshore practice: Visual, MT, UT. Additionally it must be decided if hardness tests should be performed on the weld.

As only 3 full-scale test specimens and each in a different loading condition are available for the full-scale testing a significant instrumentation, measurement, and inspection campaign will be included within the testing program.

During testing it should be monitored that the cylinders are not drifting with respect to each other. For instance, in case of combined axial and in–plane bending, the loads should be in sync, in order to avoid that after a number of cycles stresses resulting from different cylinders are counteracting each other out instead of amplifying stresses.

This effect can be mitigated partly because the stress levels at the hot spots are measured with strip gauges. And stresses and displacements are constantly measured.

Instrumentation and Measurement Program

The included instrumentation will include:
- 25 uniaxial strain gages
- 5 rosette strain gages
- (3) 5 – 5x strip strain gages
- 6 displacement sensors

In addition to the targeted instrumentation, the servo-hydraulic actuators are equipped with differential pressure sensors, to measure applied force, and displacement sensors.
The strain gages will be positioned to assess the global and local behaviors of the structure.

The global behavior being the overall loading deformations and strains away from strain/stress concentrators. The targeted local behaviors will be determination of the strain and in-turn concentration factors at the weld toes of the chord to adapter welds. The specific target region for the Axial + IPB and the OPB bending tests are: (1) Axial + IPB – brace toe and heel and (2) OPB – brace saddle points. These regions of interest will have the most intensive instrumentation efforts.

As a constant amplitude fatigue test will be conducted, the minimum-maximum values of the cycles will be recorded. Additionally, it is planned that at determined intervals complete cycles for each channel will be recorded. The measurement frequency is yet to be determined.

Inspection program

In addition to the measurement system, an inspection program is being planned. The exact inspection routine and techniques are still being evaluated; however, the proposed inspection goals, intervals and technologies will be shortly outlined.

The goals of the inspection program are as follows:
- Ensure the complete system reliability and integrity (hydraulics, supporting elements, overall K-Node structure)
- Identification of crack initiation
- Track the progression of crack growth on the surface and in the depth
- Identify the occurrence of a through thickness crack

The proposed inspection intervals, as shown I the table below, are shorter near the beginning and end of the test to focus on completely fulfilling goals 1 and 4 as these are the most critical to the overall success of the program.

Note: there is an option to do FEM analysis of crack propagation to determine what the inspection interval should be once a crack is discovered.

EUDP K-Node Fatigue Test Proposed Inspection Plan			
Interval (%)	Cycle Number	Hour Interval	Day
0%	0	0	0.0
5%	100000	28	1.4
10%	200000	28	2.8
20%	400000	56	5.6
30%	600000	56	8.3
40%	800000	56	11.1
50%	1000000	56	13.9
60%	1200000	56	16.7
70%	1400000	56	19.4
80%	1600000	56	22.2
85%	1700000	28	23.6
90%	1800000	28	25.0
95%	1900000	28	26.4
100%	2000000	28	27.8

Table 5: K-Node Fatigue Test Inspection Plan

A small amount of flexibility and variability to the exact inspection percentage should be expected such that the inspections occur at times and intervals as to maintain a continually smooth-running program.

The identified inspection techniques for the above planned inspections are a combination of visual inspection and NDT. The visual inspection being primarily for the system integrity inspections and the NDT testing to identify the crack and to track its growth. Initial considerations have identified magnetic particle testing for measurement of the crack on the surface and ultrasonic testing to be suited for measurement of the depth of the crack and identification of when the crack is through thickness.

Test procedure

Static full-scale test

First Static test to stress levels at root at 0.5xRe (yield) on the weld root (calculated from the FE model). Here the different components loadings (Axial and IPB) will be added separately and combined. This can be used to correlate with the FE model of the K-node.

Full scale fatigue test

Assumption is T curve -2SD (95% chance of crack). Stresses at weld root calculated in FEM.
Testing is continued until a trough crack has been found. For the OPB test, most probably one of the brace stub welds will fail first. It can be decided to continue the test on the other brace stub until this bracing has also fails. In that case two data points have been gathered (increasing number of specimens).
If there are no crack initiations found at the hot spots at 1.5mln cycles, then load levels are increased by 10% (still at R=0.1). This will be repeated after 0.5mln cycles.

- Cycles to failure (through crack)
- Cycles to significant crack (will be checked every day, at 1Hz this is approx. 80.000 cycles accuracy (4%).
- Crack growth: length (checked every 80.000cycles) and depth (checked every 80.000cycles).

Interpretation of results

DNV-GL-RP-0005 Appendix D-7 is used to as guidance to construct the S-N curve. The recommended practice describes a statistical approach and an engineering approach to do this. Since the number of full-scale tests is limited, the engineering approach seems most like. Here standard deviations Since the loading directions will differ between the individual K-nodes, and the different nodes are also of limited dimensions.

Small scale fatigue test

Results will give first indication of the slope of the s/N curve (m=3: crack growth dominated, m=5: crack initiation dominated) R value =0.5 for lower fatigue stress ranges, and maybe smaller for larger fatigue ranges (in this case max stress at weld toe approaches yield stress. The reason is that in real structures residual stresses will increase mean stress level. According to DNV-GL-RP-0005 this is acceptable.
Results available in appendix 3 and 4.

Construction of S/N curve

It is required that the mean curve is estimated with at least 75% confidence.
In total 3 tests are conducted with potentially 4 hotspots that will fail.

Test specimen	Manufacturer	welding	loading	hot spot location
K-node1	Bladt	stringer beads	axial + IPB	crown toe (crown heel)
K-node2	BMO	weaving	OPB	Saddle points (2x)
K-node3	Bladt	weaving	axial + IPB	crown heel (crown toe)

We should make a likelihood study: what if the weld behaves as C1 curve, and specimen's failure occurrence: 50%/85%/97.7%. What is then the chance that we can use the C1 curve for the tests. Hence, we prove that the weld behaves according to C1 curve instead of T-curve.

Results

Three full-scale and 20 small-scale tests were made to investigate the performance of semi-automatically welded joints, regarding fatigue. The experimentation was conducted by FORCE Technology.

The small-scale specimens consisted of 20 dog-bone specimens, constructed similarly to the full-scale specimens regarding the welds. The small-scale specimens were made to obtain preliminary S-N curves describing the fatigue resistance of automatically welded joints.

The full-scale specimens consisted of two different K-nodes setups and different weld types (two semi-automatically and one manually welded). The full-scale specimens were dynamically loaded to achieve fatigue failure.

Full-scale experiments

The full-scale tests consisted of three full-scale K-nodes designed as close to real life offshore wind jacket K-nodes as possible. As seen from the table, two nodes were made nearly identically due to unexpected results from the first test, which required further investigation. This is further described later in the report.

The joints between the braces and chord were in two nodes (Axial + IPB node 1 and OPB) welded using semi-automatically welding methods and for Axial + IPB node 2 fully manually welded. The tests were performed at LCST (Lindø Component and Structure Testing A/S) at Lindø in Denmark. The K-nodes were sponsored by Bladt Industries (Axial + IPB node 1), Bilfinger Mars Offshore/Salzgitter Mannesmann International (OPB) and Ørsted (Axial + IPB node 2).

Figure 6 Axial+IPB node 1 K-node.

The K-nodes were loaded with dynamic loading in a test bench capable of inducing dynamic loads up to 1600 kN. The two node geometries were loaded differently to target specific locations around the joints in fatigue. Either the crown points or the saddle points were targeted in fatigue, by introducing tension-tension loading at those specific locations. The reason for targeting single locations around the joint instead of multiple was to reduce the expected fatigue zones and thereby making it possible to obtain more reliable results which are easily correlated. The loading is shown in Figure 7 and 8 for the two node types. Note that the naming of the joints is used for the rest of the report.

For the rest of the section, the three nodes are, furthermore, denoted the Axial + IPB (node 1 or 2) and OPB node respectively, based on the loading showed in the figures.

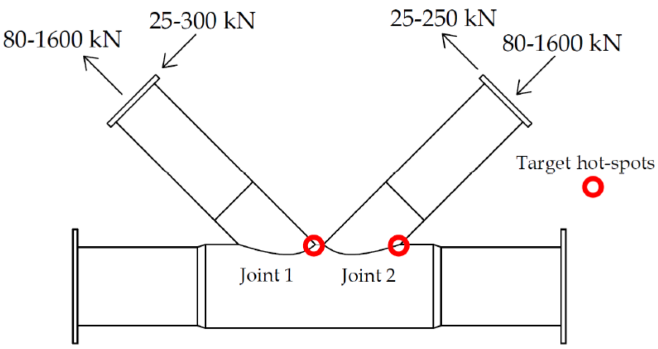


Figure 7 Axial+IPB loading.

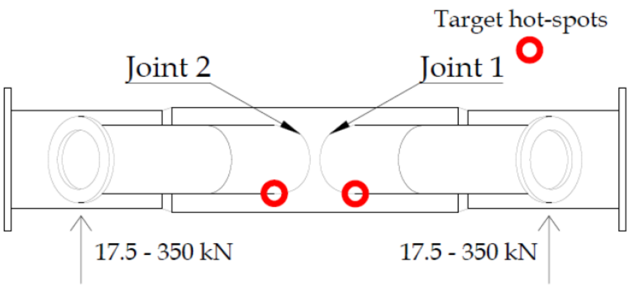


Figure 8 OPB loading

Note, that the Axial + IPB node 2, was loaded with the forces shown in Figure 7 for 2,355,797 cycles, after which it the axial loads at joint 1 was increased by rotating the axial load with 2 degrees. This resulted in a hot-spot stress increase of 10 %, as described later.

As seen from the figures above, the load range used in the tests were between R = 0.05 to R = 0.10 for the Axial+IPB node and R = 0.05 for the OPB node. These load ranges ensured that only tension-tension stresses occurred in the targeted fatigue locations. Furthermore, this ensures that residual stresses from the welding would not be lost.

The Axial+IPB node 1 and OPB node had automatically welded joints. The welds were semi-automatically welded with some manual corrections (i.e. grinding and manual welding). The welds were fabricated based on the GL Rules for Classification and Constriction 2007. The welds were manufactured using an oscillating weld torch, which results in overall better control of the weld geometry.

Strain gauge measurements

To measure the hot-spot stresses occurring in the K-nodes, strain gauges were attached on the chord and braces of all K-nodes in accordance to method “a” stated in the IIW (International Institute of Welding) recommendations. Thus, the gauges were placed at the 0.4T and 1.0T distances from the weld toe, at the expected fatigue failure locations, where T denote the base plate thickness. Therefore, the gauges are mainly placed at the crown points for the Axial+IPB node 1 and 2 and the saddle points for the OPB node. The strain gauge plans are provided in Appendix 1. Other gauges were also placed farther from the joints, to get an overall picture of the stresses and strains occurring in the K-nodes.

Small-scale experiments

The small-scale tests consisted of 20 dog-bone specimens, manufactured with similar welding as used at the saddle positions of the full-scale K-nodes. The small-scale specimens were tested by constant amplitude tensile tests in a resonance fatigue testing machine, to achieve a preliminary S-N curve. The overall geometry of the small-scale specimens is shown in the figure below. The specimens were equipped with strain gauges in correspondence to method “a” in the IIW recommendations, like the full-scale experiments. The strain gauges were placed on the small-scale specimens schematically.

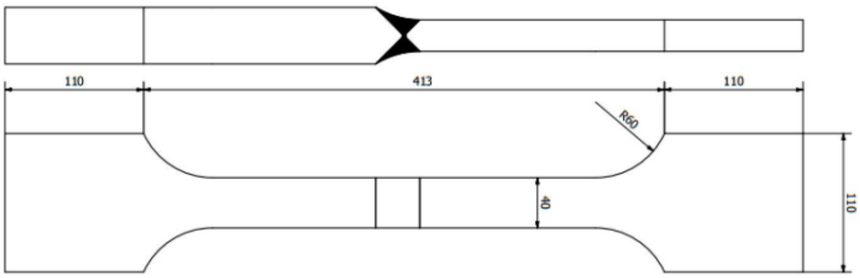


Figure 9 Small-scale dog-bone specimen

Axial+IPB Node 2 – Load Increase

During the testing of the Axial+IPB node 2, the accumulated load cycles reached an unexpectedly high value, based on the preliminary calculations. To ensure that fatigue failure in the bracechord joints and not in other undesired location such as in the test setup, the loads were increased in the joint 1 brace. As the actuator loads were already at a maximum, this was achieved by rotating the axial actuator with approximately 2 degrees, to introduce a secondary bending effect. The rotation of the axial actuator resulted in a hot-spot stress increase of approximately 10-12 percent.

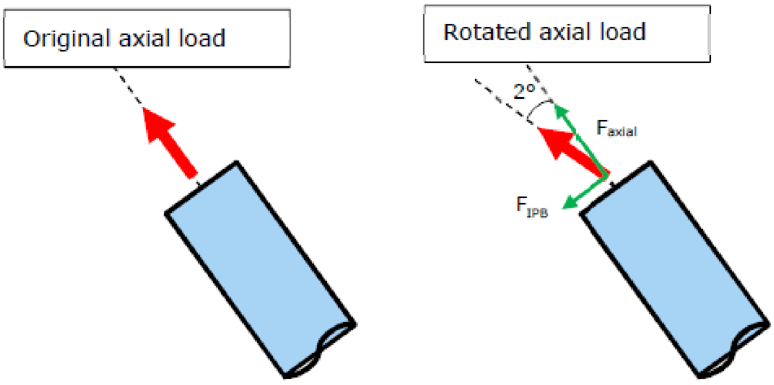


Figure 10 Schematic showing load rotation of brace at joint 1 of Axial+IPB node 2.

Rotating the load resulted in an expected cycle reduction of around 350,000 cycles, corresponding to nearly 4.5 days of test time. The rotation of the load also somewhat influences the resulting data point of the results (S-N data point). However, to include some conservatism in the results, it is chosen to use the final cycle number together with the original hot-spot stresses. I.e. the S-N data point will be lower in the S-N plot, than in reality.

Full-scale test results

The results from the full-scale testing are provided in the following section. The results consist of measured cycles until crack initiation and full through thickness crack, the measured hot-spot stresses and the measurements performed by NDT (non-destructive-testing).

The cycle number at which a first crack appeared at each joint (surface crack) and the cycle number at which a full through thickness crack was observed for each joint in all K-nodes. The cycles at which first crack and through thickness crack was found was partly based on NDT and partly based on continuous strain range measurements.

K-node	Joint	First crack	Through thickness crack
Axial + IPB node	1	[a]N/A	[a]N/A
	2	586,173	869,733
OPB node	1	1,240,000	[b]2,400,000
	2	700,095	1,632,246
Axial+IPB 2 node	[c]1	2,560,000	4,340,000
	2	[a]N/A	[a]N/A

[a] No cracks observed before test end (run-out)
[b] No through thickness crack observed before test end (run-out)
[c] At cycle number 2,355,797 the axial load was adjusted

The following should be highlighted from the table and the tests:

1) The Axial+IPB node 1 was stopped before fatigue cracks were observed in joint 1.
2) The fatigue failure location in the Axial+IPB node 1, was observed at the secondary hotspot and not primary.
3) For the OPB node, two very different fatigue lives were obtained for the joints (1.6 million and 2.4 million). Furthermore, the test was stopped before failure in joint 1 was observed (run-out).
4) The Axial+IPB node 2 showed a much higher fatigue life than the Axial+IPB node 1.
5) The through thickness fatigue cracks were observed at different locations for all nodes.

1) During the Axial+IPB Node 1 test, the fatigue test was stopped at as soon as the first through thickness crack was observed. The loads in the test bench were calibrated to allow for even loading in the K-node, thus stopping load on a single brace, would result in uneven load distributions. Furthermore, running the test with loads on both braces after the first brace had failed, would result in an unsafe situation, thus the test was stopped.

2) The Axial+IPB node 1 cracked at the secondary hot-spot (heel) and not the primary (toe). The main reason for this was found, without consideration to weld metallurgy which is investigated by FORCE

Technology, to be a big notch towards the brace in the heel. This was also found during the FE investigations.

3) For the OPB node two highly different fatigue lives were found from the braces. Note, that due to loading conditions the fatigue test could be continued even after the first brace failed. Beside the very different fatigue lives, the cracks at joint 2 were observed to start in the weld 8 profile (towards the chord) and not at the weld toe as expected. At joint 1 the cracks started, as expected, at the weld toe. The weld profile at joint 2, showed a big weld pass "bump" which explains the unexpected failure locations. This was also concluded in the FE analysis.

4) The Axial+IPB node 2 showed a much higher fatigue life than the Axial+IPB node 1. Furthermore, the fatigue failure location was at the toe (primary hot-spot) for node 2 compared to at the heel (secondary hot-spot) for node 1. The difference between the two nodes was the welding method. Node 1 was semi-automatically welded, whereas node 2 was fully manually welded.

5) The surface and through thickness cracks were observed at different locations for each node. All crack locations. The crack numbering naming below corresponds to the numbering given in the crack length and depth plots, provided later in the report.

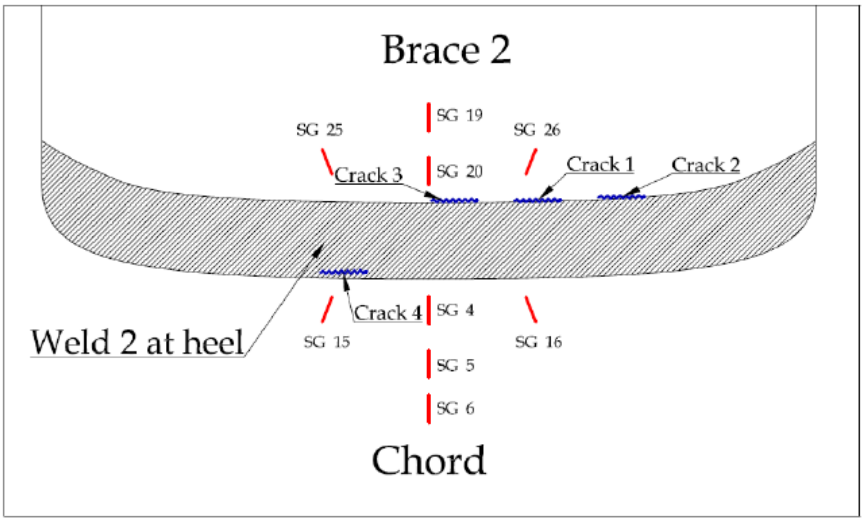


Figure 11 Schematic view of cracks at joint 2 of the Axial+IPB node. Red lines indicate strain gauges and blue lines indicate cracks.

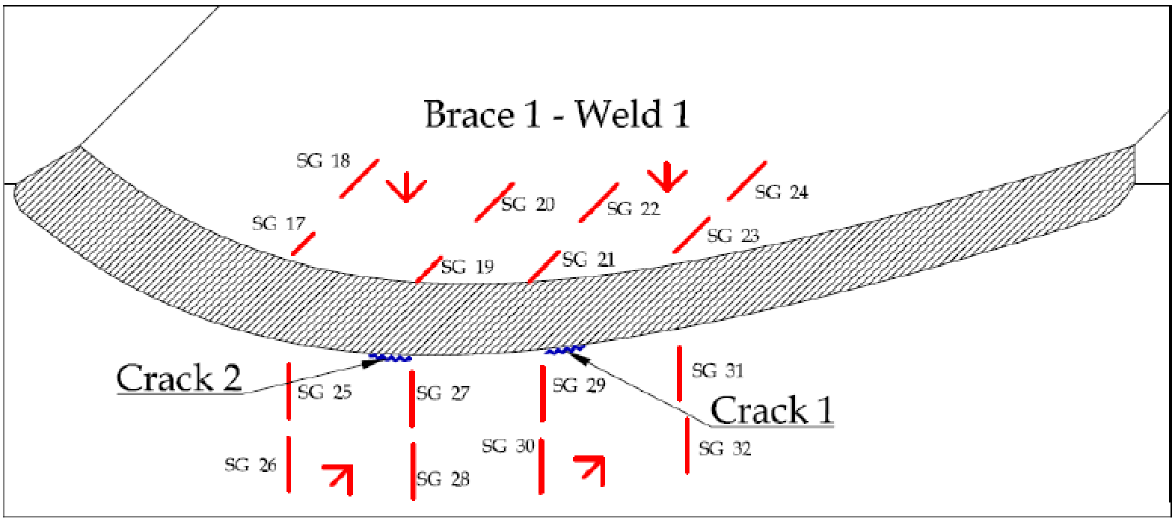


Figure 12 Schematic view of cracks at joint 1 of the OPB node. Red lines indicate strain gauges and blue lines indicate cracks.

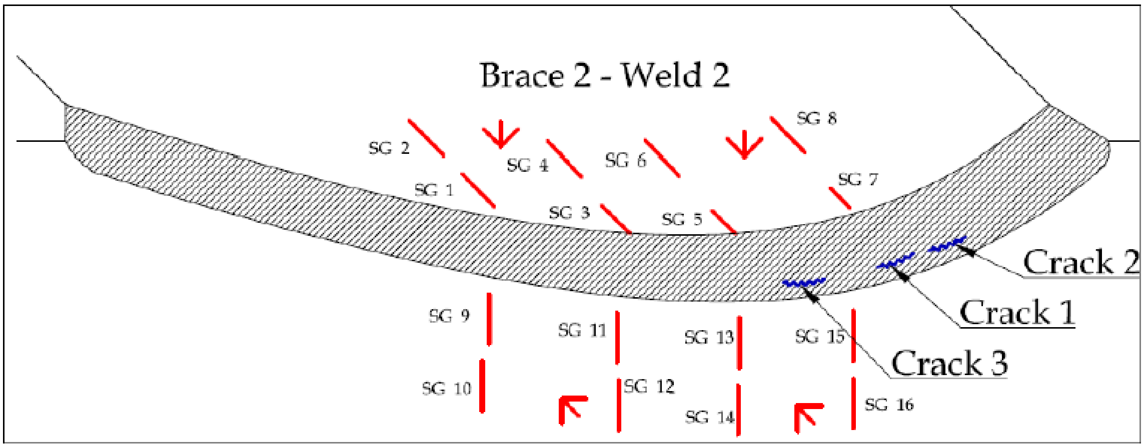
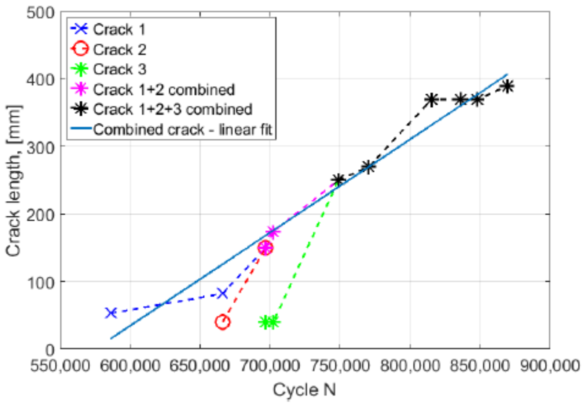


Figure 13 Schematic view of cracks at joint 2 of the OPB node. Red lines indicate strain gauges and blue lines indicate cracks.

Crack lengths and crack depths

During the testing of the full-scale specimens the crack lengths and crack depths were continuously measured using NDT techniques (MT and UT). Note that some cracks joined during the test and not all cracks were monitored in depth. Both the crack depths and crack lengths show linear trends, wherefore linear regression have been made for all measurements. Note that for the crack lengths only a single linear regression based on the combined crack length, has been made.



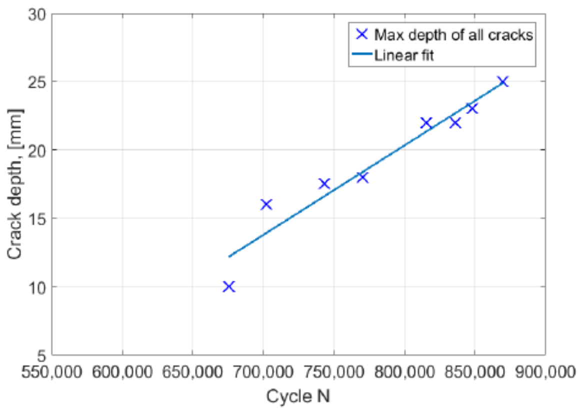
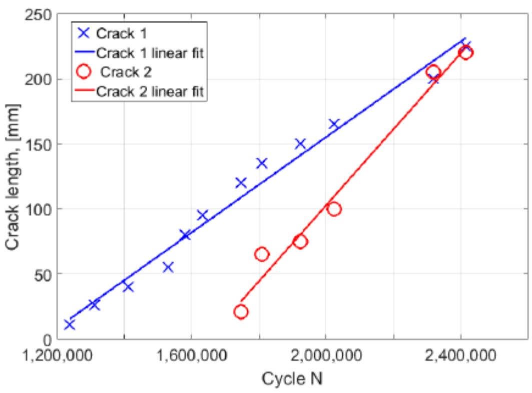


Figure 14 Crack lengths (left) and crack depths (right) of Axial+IPB node (joint 2).



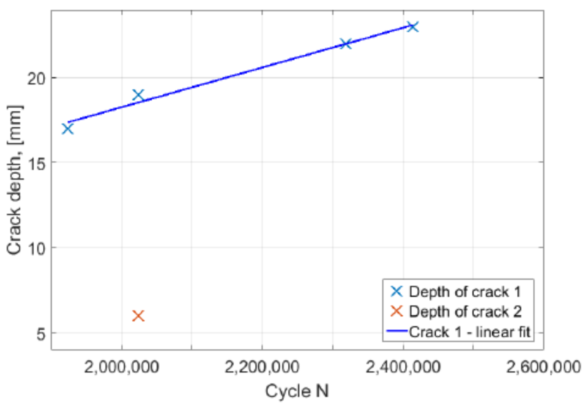


Figure 15 Crack lengths (left) and crack depths (right) of OPB node (joint 1).

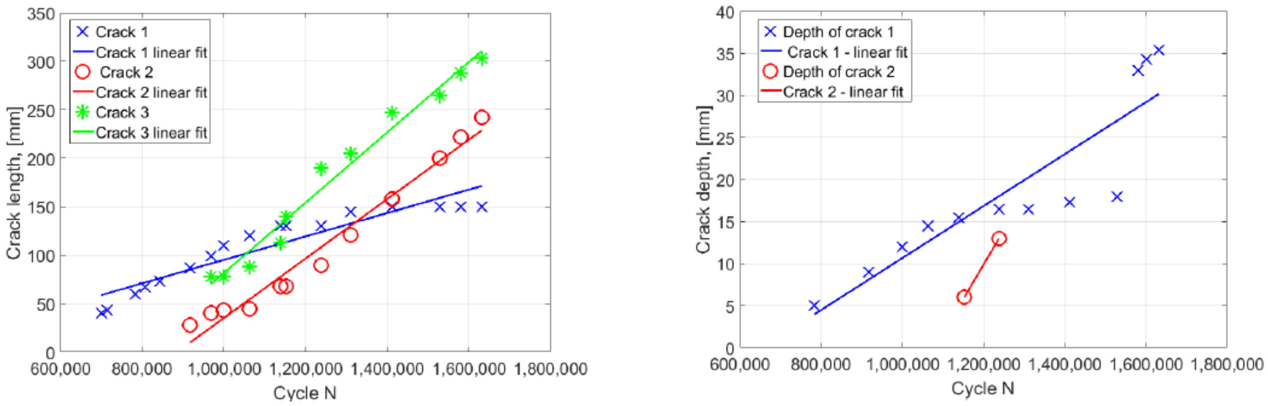


Figure 16 Crack lengths (left) and crack depths (right) of OPB node (joint 2).

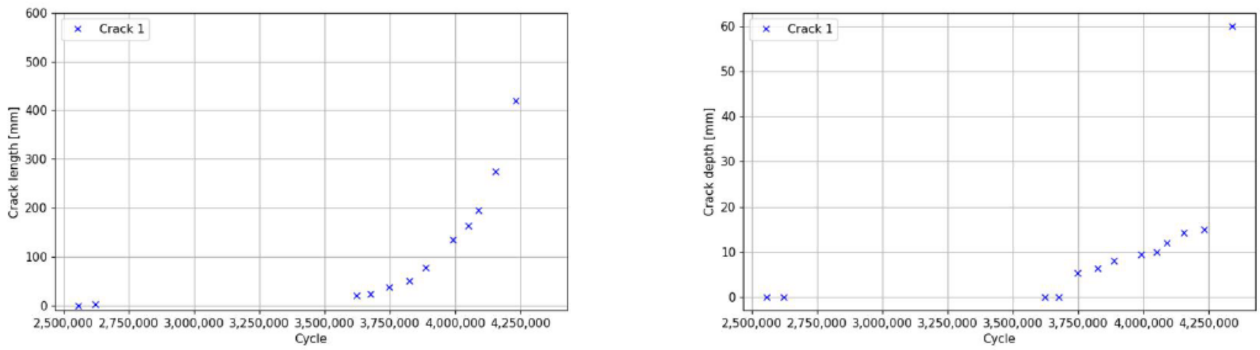


Figure 17 Crack lengths (left) and crack depths (right) of Axial+IPB node 2 (joint 1).

As seen from the figures above, the crack lengths grew faster than the crack depths.

To show the slopes of all measurements combined, all linearization's are plotted with crack lengths and crack depths in the figures below.

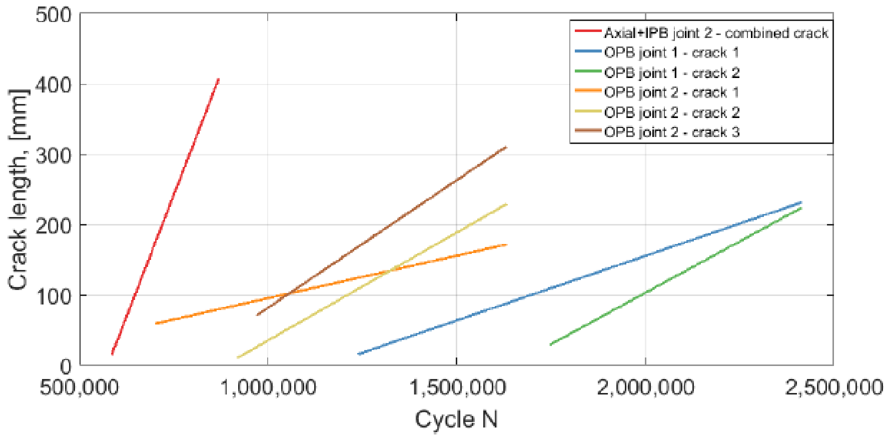


Figure 18 Comparison of linearized crack length curves.

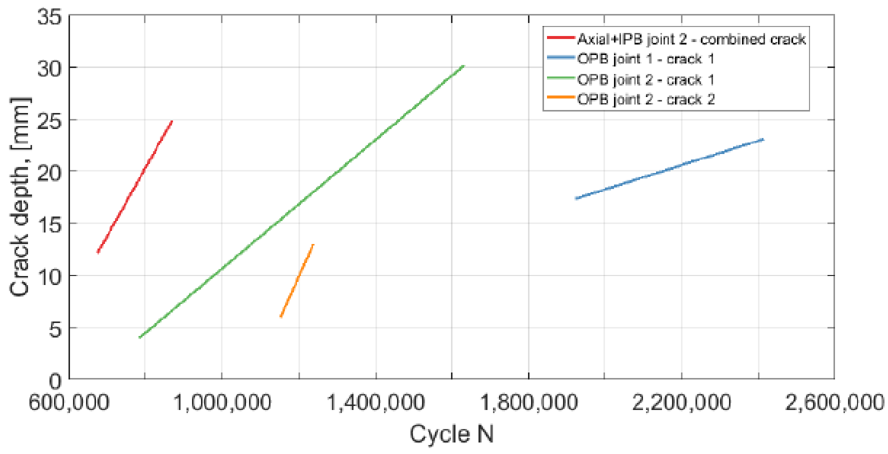


Figure 19 Comparison of linearized crack depth curves.

As seen from the results, conclusions cannot easily be obtained based on the small amount of data, due to only two K-node tests. However, it is easily seen that the crack grew much faster in the circumferential direction (on the surface), compared to in depth. This is most likely explained by the residual stresses which are present after welding the joints.

Small-scale test results

The small-scale results are listed in the following section. Both the nominal and hot-spot strain ranges were documented by FORCE Technology. The results are therefore the nominal stress range results and hot-spot stress range results, respectively. The tests are shown with cycle number at fatigue failure and corresponding stress range. Note that some tests were discarded, wherefore the total number of 20 experiments are not present and that the run-outs were excluded from the hot-spot results.

Based on the small-scale results, FORCE Technology developed two S-N curves (each with a mean and design curve). FORCE Technology states that these parameters should be used together with the DNVGL-RP-C203 method of fatigue strength reduction due to base plate thickness from this design code. The resulting S-N curves are plotted together with the data samples.

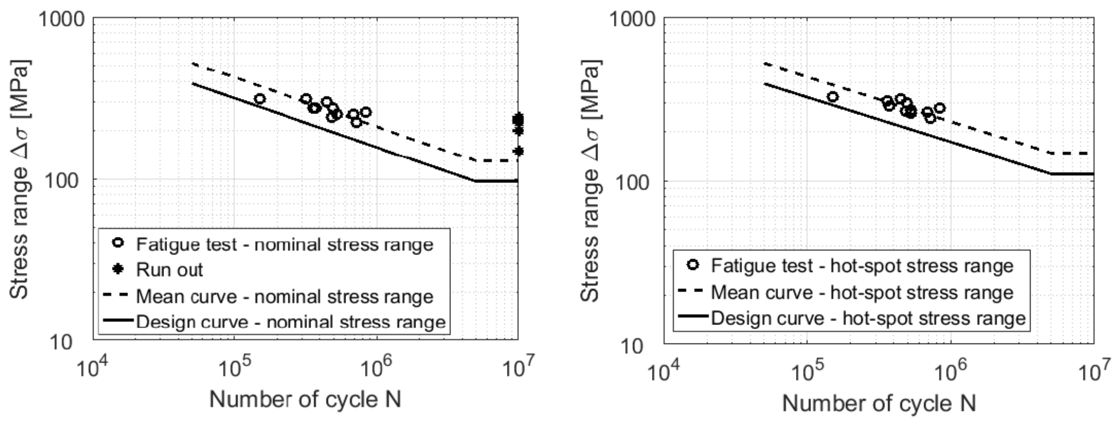


Figure 20 Generated S-N curves for small-scale specimens. Nominal S-N curve (left) and hot-spot S-N curve (right)

Fatigue assessment

The following section consists of the fatigue assessment and generation of S-N curves based on the test results from the project. All test results, from both the small-scale and full-scale specimens, are plotted together. Only the hot-spot fatigue results are shown from the small-scale tests. Furthermore, the mean and design S-N curve obtained from the small-scale testing and the mean and design T curve, from the DNVGL, are plotted.

It should be noted, that the data point for the Axial+IPB node 2, has been taken as the crack cycle and the hot-spot stress from the first load appliance. The load was changed during the testing to achieve higher hot-spot stresses and thereby reduce the testing time. However, for the data assembly below, the smallest hot-spot stress is used for simplicity. This is a conservative assumption as the data point will be lower in the S-N curve than in reality.

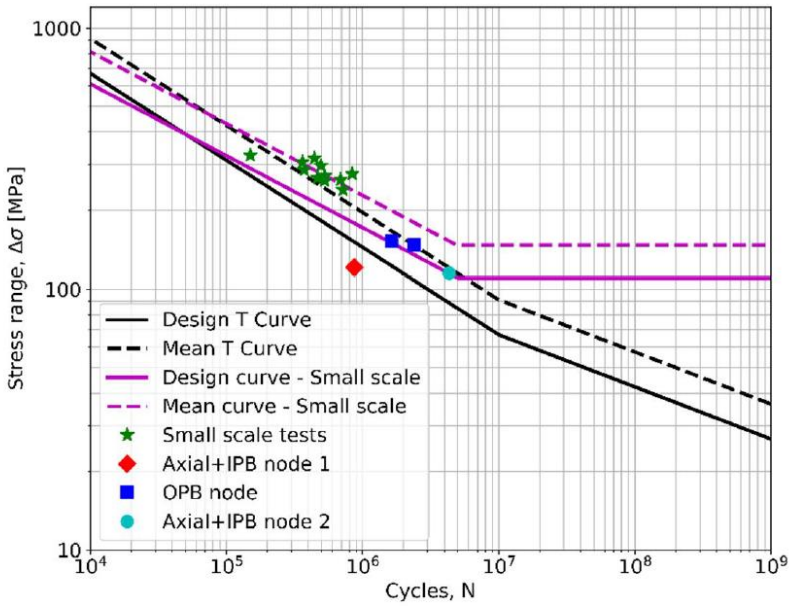


Figure 21 Fatigue results from small-scale and full-scale test specimens plotted together with small-scale obtained S-N curves and DNVGL T-curve

The above figure shows all acquired fatigue results from both the full-scale and small-scale specimens, without considering any reduction due to base plate thicknesses (thickness effect), which is proposed by e.g. the DNVGL-RP-C203. As Figure 21 do not consider reduction in fatigue life due to base plate thickness (thickness effect), the results are plotted again in Figure 22, Figure 23 and Figure 24 below, where the thickness correction is included. In Figure 22, the result from the Axial+IPB node 1 is
plotted against the design and mean curve obtained from the small-scale specimen tests and the DNVGL T-curve. Both curves are reduced due to the base plate thickness, as by the recommendations from the DNVGL for tubular joints. In the Axial+IPB node 1 the failure was observed at the brace side of the node, wherefore the base plate thickness used in the reduction is 25 mm. In Figure 23, the results from the OPB testing is shown, together with the different S-N curves (with both mean and design curves). In the OPB test the failure was observed to happen towards the chord side of the K-node, wherefore the base plate thickness is set to 70 mm. Lastly, in Figure 24, the results from the Axial+IPB node 2 are plotted against the respective S-N curves. In this test, the cracks were observed to start towards the chord side, thus the thickness effect of a 60 mm thick chord is included in the S-N curves.

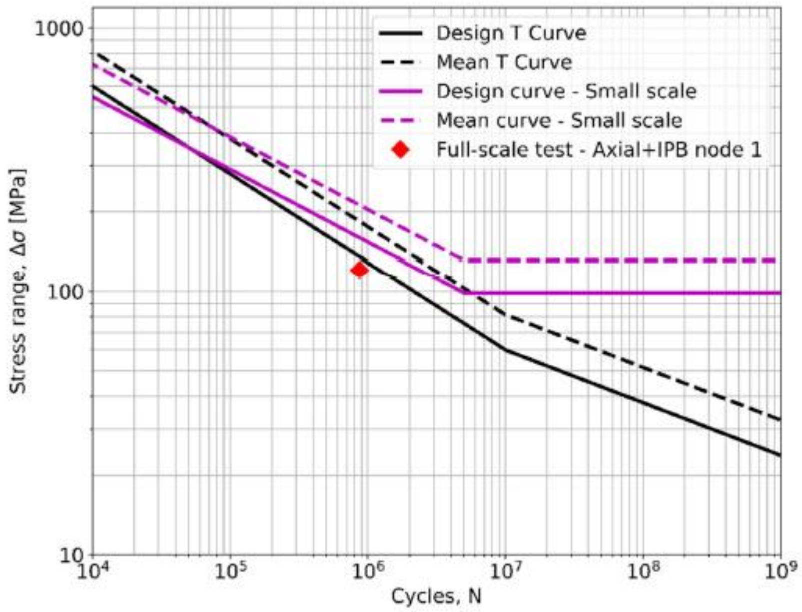


Figure 22 S-N results from Axial+IPB node 1 experiment plotted together with S-N curve from smallscale experiments and T-curve, both corrected for based plate thickness of 25 mm.

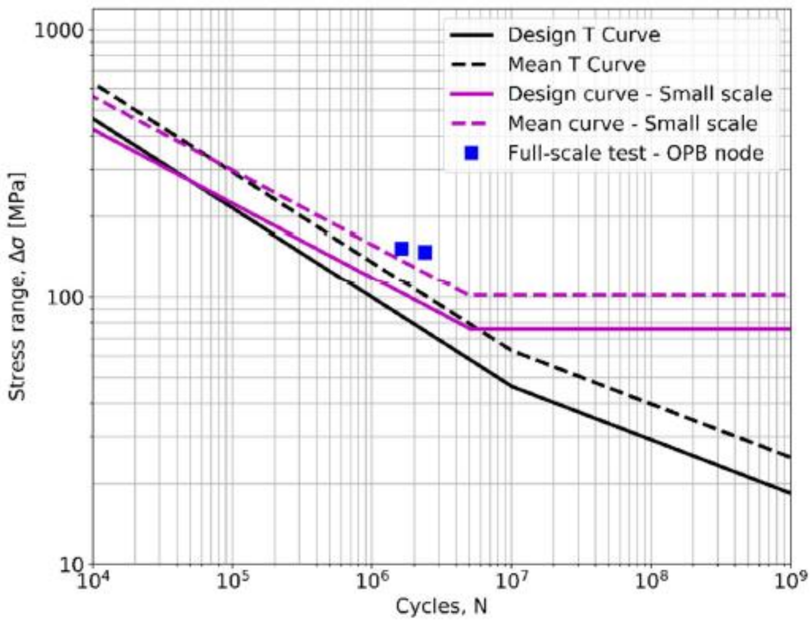


Figure 23 S-N results from OPB experiment plotted together with S-N curve from small-scale experiments and T-curve, both corrected for based plate thickness of 70 mm.

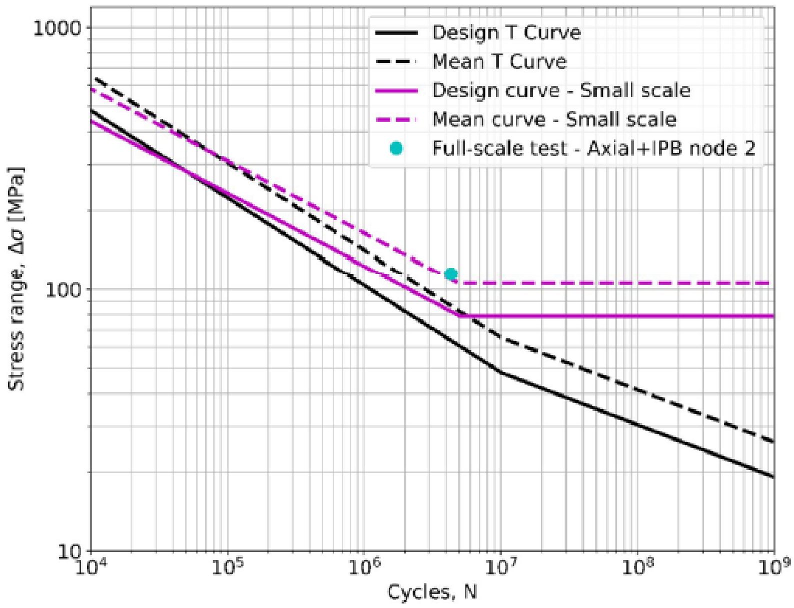


Figure 24 S-N results from Axial+IPB node 2 experiment plotted together with S-N curve from small-scale experiments and T-curve, both corrected for based plate thickness of 60 mm.

The results show that the Axial+IPB node 1 exhibits much lower fatigue life than what was expected, being just below the T-design curve. The other two nodes, however, show results quite close to the mean small-scale curve. As the OPB node and the Axial+IPB node 2 are manufactured using different welding techniques nothing can be concluded on this.

Comparison of generated S-N curves and final curve details

The following section serves to compare the S-N curves generated for the tubular joints with semi-automatic welding

All design curves are shown in the figure below, without any thickness reduction. In Figure 26, all curves are shown together with the full-scale OPB results (including thickness effect, 70 mm). In Figure 27, all curves are shown together with the Axial+IPB node 1 result (including thickness effect, 25 mm).

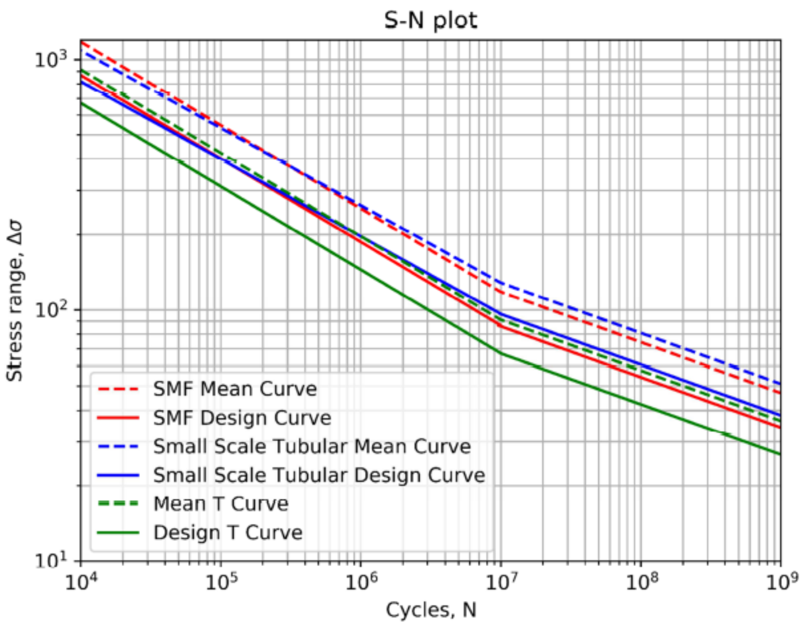


Figure 25 All S-N curves plotted together

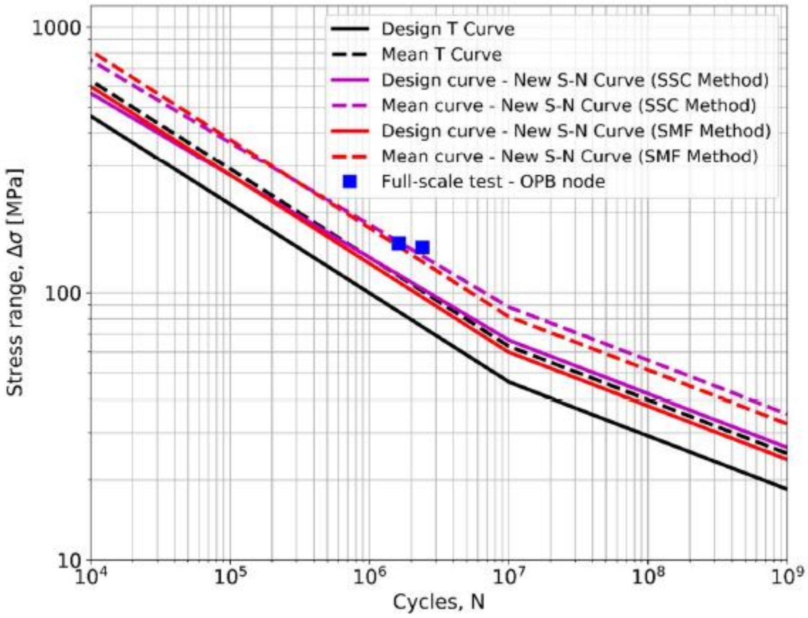


Figure 26 S-N curves plotted together with OPB results (thickness effect included).

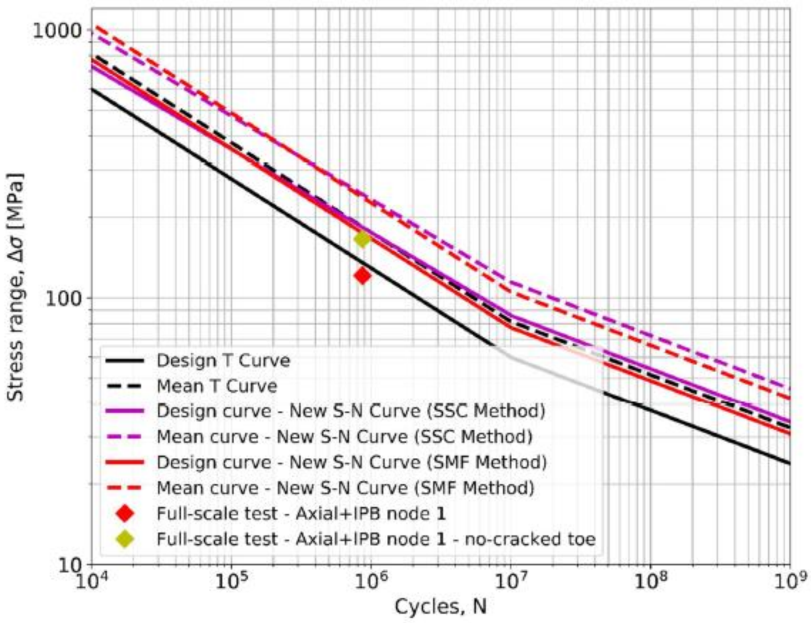


Figure 27 All S-N curves plotted together with Axial + IPB node 1 results (thickness effect included).

In the figure where all curves are plotted together, Figure 25, it can be seen that the two different methods used for predicting S-N curves based on the SMF method and entirely on the small-scale specimens, are very close to each other, indicating the methods being usable and consistent. Furthermore, as seen from the plots, the new curves are showing much higher fatigue lives than the original T-curve. It can also be seen that the S-N curve based on the small-scale specimens are more conservative in the low cycle life compared to the high cycle life. Looking into Figure 26, it can be seen that the results of the OPB full-scale test fit nicely to the new S-N curves, which also makes sense for the SMF curve as this is based entirely on the OPB results. The S-N curve based on the small-scale results, however, show nearly the same curve as the SMF curve, indicating that the two methods of generating S-N curves are very consistent.

As seen from Figure 27, the Axial+IPB node 1 results are below both the mean and design SMF and small-scale S-N curves. This is unfortunate, as it indicates that the curves cannot be used generally for tubular joints with semi-automatic welds. However, it should be noted that the test result also is below the design T-curve. This could indicate that the Axial+IPB node 1, was manufactured poorly, as it could be estimated that it at least should have shown results abovethe design T-curve, due to improvements in the welds, which was expected. Also, comparing the curves to the uncracked hot-spot (joint 1 at the toe), which did not fail before the test end, it can be seen that this data point is just below the mean T-curve and design SMF and small-scale curves, which also indicates that some underlying problem was the cause of the cracking at joint 2 in Axial+IPB node 1.

Comparison to Axial+IPB Node 2

As the Axial+IPB node 2 was not manufactured using semi-automatic welding techniques it does, in principle, not make sense to compare the results from this node to the new generated S-N curves. However, as the preliminary visual investigations of the semi-automatically showed somewhat worse weld profiles than what could be expected from manual welding, it makes sense to compare the results from the Axial+IPB node 2 to the new S-N curves anyway. This will also show if the discovered improvements are due to overall weld quality improvements or something else. The result is plotted below in Figure 28. Note, that due to the Axial+IPB node 2 cracking towards the chord instead of towards the brace, the results cannot be plotted together with the results from the Axial+IPB node 1.

As seen from Figure 28 the result from the Axial+IPB node 2, lies very close to the newly generated mean S-N curves. This could suggest an overall improvement in welding procedures, not due to either automatic or manually welding. However, as no more experiments are conducted, this cannot be investigated further.

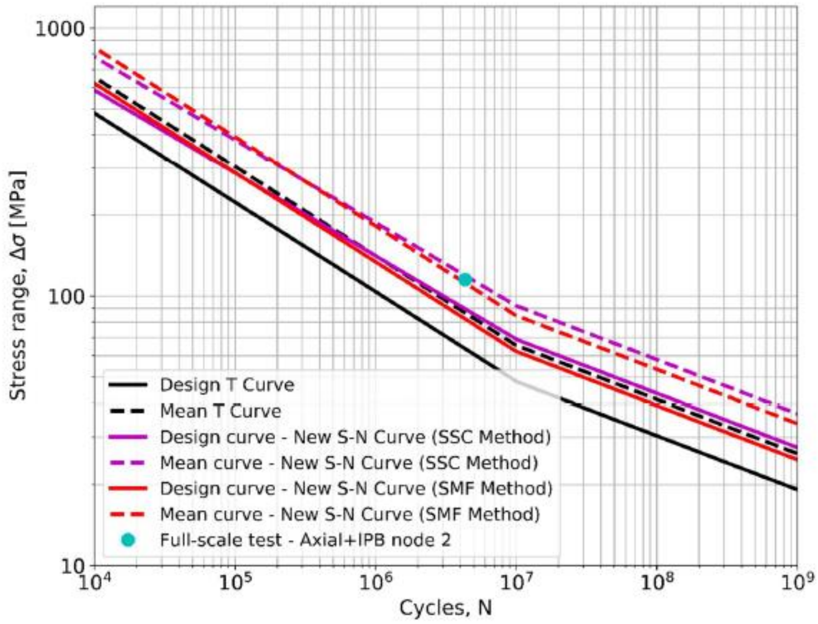


Figure 28 All S-N curves plotted together with Axial+IPB node 2 results (thickness effect included).

Case study of 10 MW DTU jacket with new S-N curves

In order to give an estimate of the actual fatigue life improvements using the newly generated SN curves, a case study has been made using the DTU 10 MW jacket, which is opensource.

Ramboll has, as part of the INNWIND project, a full design model of the DTU 10 MW jacket. To check the possible benefits of the new dedicated S-N curves, two base models have been compared. The base models are listed in the table below. The first model, consists of the original jacket structure which predicts the fatigue lives in the nodes, using the standard T curve (air) from the DNVGL-RP-C203. All nodes, including the submerged and the nodes located in the splash zone, is calculated using the air curve.

This is done as the model is used for comparison only, and as the EUDP generated S-N curves from the full-scale experiments only are applicable in air. The second model, model 2, is the original DTU 10 MW jacket structure, but the fatigue lives of the nodes are calculated using the newly generated SMF curve.

Base model	S-N curve used for nodes
Model 1 – Original Jacket	DNVGL T curve (air)
Model 2 – Updated S-N curves	EUDP SMF curve (air)

The results are provided for the node located in level 40, denoted 40A0P0 for the DTU 10 MW jacket.

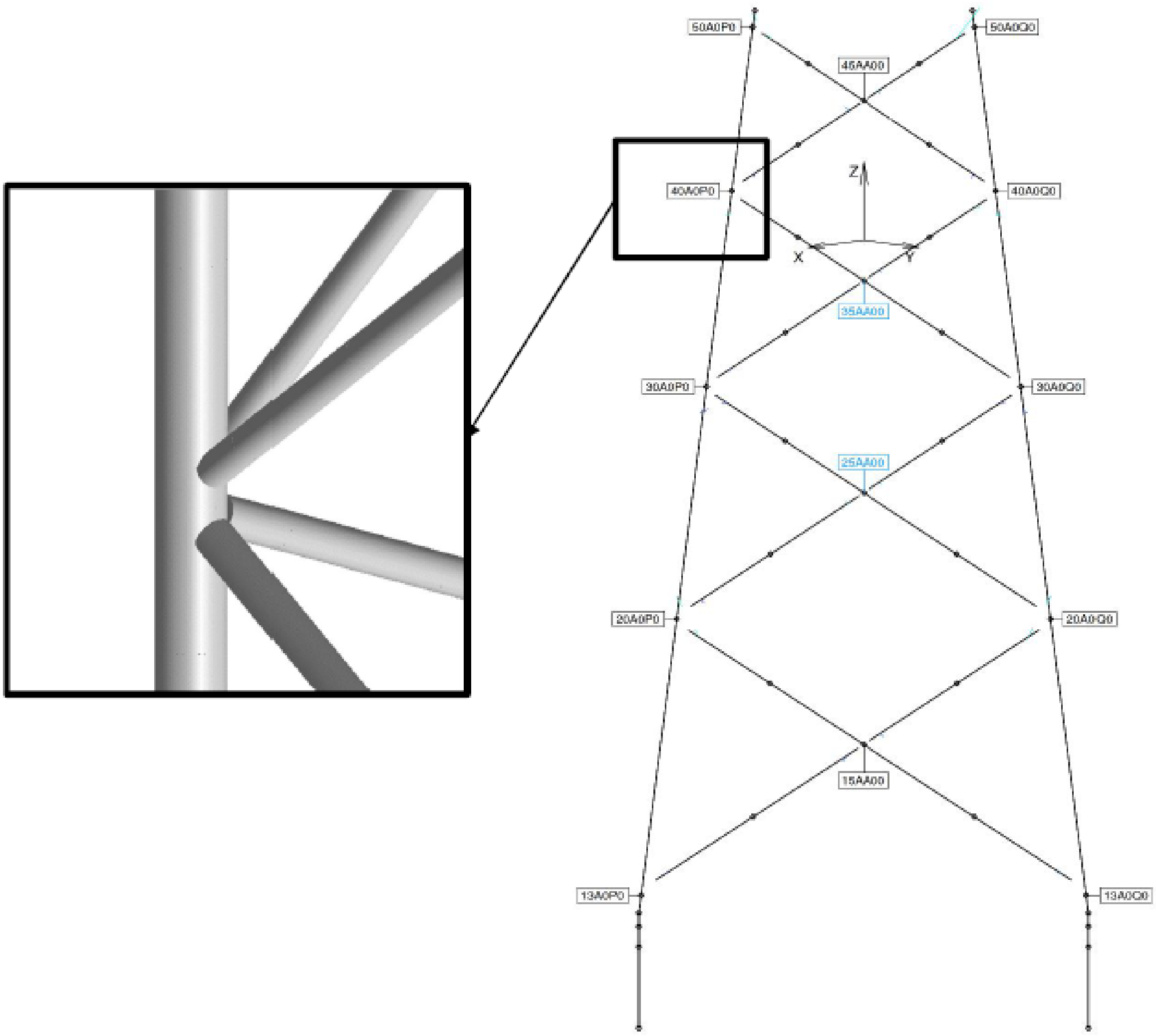


Figure 29 Node 40A0P0 from DTU 10 MW jacket.

The results from the calculations using the standard T-curve and the EUDP SMF generated curve are provided below. As seen from the results, using the standard curve and a chord with a thickness of 51.8 mm results in a fatigue life of 33 years. Using the EUDP SMF curve instead results in a fatigue life of over 900 years. Reducing the thickness with 14 percent (to 44.4 mm), results in a fatigue life of 94 years. Thus, using the new S-N curve, could result in large savings in chord thicknesses (and possibly other dimensions). Failure at braces have not been considered at this stage and only the chord thickness has been varied. However, the results still show a massive improvement in fatigue lives.

SN-Curve	Chord Thickness	Calculated fatigue life
Standard T-curve (air)	51.8 mm	33 years
EUDP SMF curve (air)	51.8 mm	958 years
	44.4 mm	94 years

Conclusions on fatigue tests

The fatigue tests focused on the use of semi-automatic welded joints in offshore jacket structures, which was believed to show a better fatigue performance than joints welded with traditional methods. A final test was, however, also made using traditional welding methods.

The geometry of the test specimens, measurement equipment, non-processed and processed results are provided. Based on 20 small-scale fatigue tests, preliminary S-N curves for joints welded using automatic welding procedures were manufactured by FORCE Technology. The S-N curves generated from the small-scale specimens were compared to the tubular joint S-N curve from the DNVGL-RPC203, which showed that improvement in fatigue life could be expected for semi-automatically welded tubular joints.

Three full-scale K-node structures were manufactured, and fatigue tested at LCST at Lindø. The three nodes were manufactured with only small overall geometric differences and were tested in out-of-plane bending or axial+in-plane bending, which targeted different locations around the welded joint in fatigue. Two nodes were made with semi-automatic welding techniques and the last node was made with fully manual welding. The results from the fatigue tests consisted of hot-spot strain measurements, cycles to crack initiation and through thickness cracks and crack locations. The results indicated that the first node loaded with axial and in-plane bending, cracked prematurely, wherefore it for the S-N curve generations were excluded as a data point. The fatigue life from the second Axial+IPB node was also much higher than the for the first node, also indicating some premature failure in the first node.

S-N curves were generated for semi-automatic welded joints based on the conducted small and full-scale fatigue tests, using two different methods. The first method was the, in this report denoted, SMF method which is described in the DNVGL-RP-C203. The other method was based solely on the small-scale test results. The developed S-N curves showed good compliance with each other and comparing them to the full-scale OPB results showed very good consistency. Comparing the curves to the Axial+IPB node 1 results, however, did not show the same good results as the fatigue life of this node was well below both the mean and design curves. However, the fatigue life was also lower than the standard T-curve from the DNVGL-RP-C203, which again indicated that some premature failure was observed from the results. The comparison between the new S-N curves and the second Axial+IPB node, which was manually welded, showed good consistency. This could, to some point, indicate that the actual increase in S-N curve is not due to the OPB nodes being semi-automatically welded, but perhaps that the overall welding techniques and methods are improved compared to when the first S-N curves were developed.

Applying the newly generated S-N curves to a base case of the DTU 10 MW jacket, showed an improvement in fatigue life of 900 years or reduction in chord thickness of 14 percent, when utilizing the new S-N curve.

Coating systems for offshore jacket design

The cost of offshore wind has to be lowered to ensure profitable investments for the owners of the offshore wind farms. The novel Siemens Wind Power (SWP) jacket foundation concept includes the use of standard pipes from the line pipe production, and selected corrosion protection systems already in use at the pipe manufactures. At the same time the SWP concept aims at extending the "useful service life" of the corrosion protection system, from the present 20 years to future 25 years, which equals the service lifetime of the wind farm. This test program focuses on coating systems for immersed and splash zone services. With a foundation in ISO 20340 and partly NACE TM 0404, leading actors in the pipe coating industry have been invited to join this project with relevant coating systems. The splash zone ISO 20340 system prescribes ≥ 600 µm and the immersed service system ≥ 350 µm, both to be applied in two coats.

The aim of the coating system analysis is to compare conventional coating systems based on wet paint technology with fusion bonded epoxy technology with special attention to the application in offshore environment. In the analysis, relevant test protocols have been selected to evaluate the suitability of the coating systems for service in immersed and in splash zone conditions.

Test plan

During the fall 2015, Siemens WP and FORCE Technology have prepared a test package, which is believed to cover the most important test parameters for coating systems serving in offshore environments. To get a balanced assessment on both accelerated weathering and the coating systems' mechanical properties, it was decided to combine ISO 20340 (exposure testing) with parts from NACE TM 0404 (mechanical testing). To our best knowledge, this is the first time that FBE systems and wet paint systems are being tested together against ISO 20340 and NACE TM 0404. Panel replicates are made to fulfil the 3 replicate requirements per test (except that of the Impact test, for which all readings can be made on the same panel). In addition to this, it was agreed to extend the ISO 20340 test from 6 to 9 months, meaning that 6 panels are needed for ISO 20340 testing. Leading players in the pipe coating industry have been invited to join this project with relevant coating systems. For the splash zones ISO 20340 prescribes ≥ 600 µm and for immersed service ≥ 350 µm, both systems to be applied in two coats.

The coating systems include wet epoxy systems with polyurethane top coat (systems 1 and 2), wet epoxy systems without polyurethane topcoat (systems 7, 8, 9 and 10) various Fusion Bonded Epoxy coating systems (systems 3, 4, 5, 11, 12, 13 and 15) and two glass flake polyesters (systems 6 and 14).

ISO 20340	Seawater Immersion	Cathodic Disbondment	Mechanical Tests		
			NACE TM 0404	NACE TM 0404	NACE TM 0404
Ageing (9 months)	IMS (9 months)	CBT (9 months)	MAN	IMP	TCT
Start: March 22, 2016	**Start:** March 22, 2016	**Start:** April 05, 2016	**Start/Stop:** March 18, 2016	**Start:** March 19, 2016 **Stop:** April 07, 2016	**Start:** March 15, 2016 **Stop:** April 06, 2016
3 months evaluation: June 22, 2016	**3 months evaluation:** June 22, 2016	**3 months evaluation:** July 05, 2016			
Visual inspection	Visual inspection	Visual inspection			
6 months evaluation: September 22, 2016	**6 months evaluation:** September 22, 2016	**6 months evaluation:** October 04, 2016			
Measurement of scribe: September 23, 2016 Pull of test: October 5-6, 2016	Measurement of scribe: September 23, 2016 Pull of test: October 5-6, 2016				
9 months evaluation: December 22, 2016	**9 months evaluation:** December 22, 2016	**9 months evaluation:** January 04-05, 2016			
Measurement of scribe: December 23, 2016 Pull of test: January 5-6, 2016	Measurement of scribe: December 23, 2016 Pull of test: January 5-6, 2016				

Results

Dry film thickness

The dry film thickness (DFT) readings may be found in Appendix A. All panels applied with AkzoNobel coating systems have been arranged and applied by Europipe & S.M. Forschung and Muelheim Pipe Coatings, who also took care of the surface preparation. All other coating systems were applied by Jakob Albertsen (JA). The QC reports from JA may be found in Appendix B. FORCE Technology was partly present during the application of wet paints and the FBE coatings at JA and during the final selection of test panels (based on visual appearance and dry film thickness, DFT). During the selection of the panels to be tested, it was noted that in general, the DFT readings were at the high end and formally do not meet the strict restrictions according to ISO 20340 (max DFT < 1.25xNDFT). However, for the test package the most uniform DFT distributions among all panels (and coating technologies) were selected and at the same time aimed at an average value close to the specified DFT. All test results will have a reference to the actual DFT on the test panel. About the NACE thermal cyclic testing, it was noted that the panels supplied with the AkzoNobel systems are different from the geometry specified by Siemens.

Mechanical test according to NACE TM 0404

The following mechanical tests were performed: Impact test (ISO 6272-2/ASTM D2794), Thermal Cycling Resistance Test and Flexibility test (Hydraulic Mandrel Bend test). In general, all coating systems performed well in the mechanical testing. However, some trends were observed, which are described in the following.

System #	Panel #	System code	TDFT	Impact value [in. lb.]
1	1-IMP-1	SF_EP1	680 µm	>126
2	2-IMP-1	SF_EP2	680 µm	110
3	3-IMP-1	FBE3	700 µm	>126
4	4-IMP-1	FBE4	680 µm	>126
5	5-IMP-1	FBE5	680 µm	>126
6	6-IMP-1	GF6	1000 µm	40
7	7-IMP-1	SF_EP7	350 µm	40
8	8-IMP-1	STD_EP8	600 µm	40
9	9-IMP-1	SF_EP9	600 µm	65
10	10-IMP-1	SF_EP10	600 µm	35
11	11-IMP-1	FBE11	600 µm	>126
12	12-IMP-1	FBE12	600 µm	>126
13	13-IMP-1	FBE_Zinc13	680 µm	123
14	14-IMP-1	GF14	1200 µm	81-90
15	15-IMP-1	FBE15	680µm	>126

Figure 30 Results from Impact Test (performed 7-8/4-2016)

The FBE systems (systems 3, 4, 5, 11, 12 13 and 15) performed better in the impact test than the wet epoxy (systems 7, 8, 9 and 10) and the glass flake systems (systems 6 and 14). Exceptions were the wet epoxy systems top coated with a polyurethane (systems 1 and 2), which showed performance on par with the FBE systems.

System #	Panel #	System code	DFT (side 1) (mean)	DFT (side 2) (mean)	Location of cracks
1	1-N-TC-1	SF_EP1	759±62	722±74	No cracks
	1-N-TC-2		659±54	550±43	No cracks
	1-N-TC-3		833±48	684±51	No cracks
2	2-N-TC-1	SF_EP2	736±66	787±44	No cracks
	2-N-TC-2		826±56	930±103	No cracks
	2-N-TC-3		922±46	806±97	No cracks
3	3-N-TC-1	FBE3	678±60	816±61	No cracks
	3-N-TC-2		853±30	756±49	No cracks
	3-N-TC-3		808±20	859±70	No cracks
4	4-N-TC-1	FBE4	840±42	788±149	No cracks
	4-N-TC-2		1015±66	985±81	No cracks
	4-N-TC-3		765±95	682±65	No cracks
5	5-N-TC-1	FBE5	888±39	1043±173	No cracks
	5-N-TC-2		778±49	786±80	No cracks
	5-N-TC-3		903±57	808±98	No cracks
6	6-N-TC-1	GF6	1260±28	1560±142	Cracks in corner
	6-N-TC-2		1215±44	1490±138	Cracks in corner
	6-N-TC-3		1260±28*	1650±156*	Cracks in corner
7	7-N-TC-1	SF_EP7	299±67	279±43	No cracks
	7-N-TC-2		207±102	253±24	No cracks
	7-N-TC-3		274±14	310±46	No cracks
8	8-N-TC-1	STD_EP8	690±91	832±55	No cracks
	8-N-TC-2		794±21	801±45	No cracks
	8-N-TC-3		736±57	744±54	Small cracks in corner
13	13-N-TC-1	FBE_Zinc13	849±63	987±86	No cracks
	13-N-TC-2		1018±108	987±104	No cracks
	13-N-TC-3		1127±64	1189±70	No cracks
14	14-N-TC-1	GF14	350->1500*	350->1500*	Crack (FORCE indicat.)
	14-N-TC-2				No cracks
	14-N-TC-3				No cracks
15	15-N-TC-1	FBE15	586±43	-	Small cracks in corner
	15-N-TC-2		529±23	540±81	No cracks
	15-N-TC-3		492±7	548±35	No cracks

Figure 31 Results from NACE Thermal Cycling Test (performed 16/3 to 6/4 2016).

In general, no cracks were observed on any system except on the glass flake systems. In this respect, it should be noted that cracks were only detected in the corner. In addition to this, one of the glass flake systems (system 14) was in black color, making evaluation for cracks difficult. Therefore, for the two-glass flake systems FORCE Technology recommends either 1) to neglect the results from the TCT or 2) to redo the test with correct DFT distribution and both coating types applied in light shade. Only system 8 (epoxy reference) and system 15 (FBE) showed small cracks in the corner on one of the replicate panels.

System #	Panel #	System code	Mandrel diameter [mm]	Relative elong. [%]	Pinhole det. (Low voltage)
1	1-N-FX-1 to 5	SF_EP1	88,5; 118,5; 142,5;	1,6	No pinholes
2	2-N-FX-1 to 5	SF_EP2	88,5; 101,4; 118,5; 178,5;	2,0	No pinholes
3	3-N-FX-1 to 5	FBE3	24,2; 34,5; 38,5; 49,9; 58,5; 88,5	>8	No pinholes
4	4-N-FX-1 to 5	FBE4	118,5; 142,5	1,8	No pinholes
5	5-N-FX-1 to 5	FBE5	88,5; 101,4; 118,5; 142,5; 178,5	1,7	No pinholes
6	6-N-FX-1 to 5	GF6	178,5; 238,5; 358,5	0,8	No pinholes
7	7-N-FX-1 to 5	SF_EP7	58,5; 70,5; 88,5	2,1	Pinholes on panel 3
8	8-N-FX-1 to 5	STD_EP8	118,5; 142,5; 178,5	1,3	no cracks observed but Pinholes on panel 1, 2, 5
13	13-N-FX-1 to 5	FBE_Zinc13	88,5; 101,4; 118,5; 142,5	1,8	No pinholes
14	14-N-FX-1 to 5	GF14	178,5; 358,5	< 0,5	No pinholes
15	15-N-FX-1 to 5	FBE15	58,5; 70,5; 88,5; 101,4; 118,5	2,6	No pinholes

Figure 32 Results from NACE Flexibility Test (Mandrel), performed 16/3 to 17/3 2016.

The wet epoxy and the FBE systems showed an expected flexibility of about 2 %. One exception was system 3 (FBE Jotapipe AC1003 (1x600µm) + Jotapipe DL3003 (100µm)) with very high elongation, >8%. It should be noted, however, that there is a chance that the top coat hides potential cracks in the epoxy primer. Destructive testing of the panel/coating system is necessary to confirm this thesis. The glass flake systems showed a slightly lower flexibility (< 1 %), which is also to be expected for that technology.

All systems pass the immersion test showing no blistering, no rust and the rust creep from the scribe is well below 8 mm (3 mm for zinc primed systems). An unusual behavior of FBE_Zinc13 was observed already during the 3 months' evaluation: A heavy build-up of corrosion products is observed around the scribe, despite the fact that no rust creep from the scribe is detected. So far, no explanation for this phenomenon has been found, however the pattern of the corrosion suggests that the more or less intact zinc primer in the scribe seems to act as a cathode, while corrosion in fact attacks the steel substrate forming a deep groove. Whether the zinc primer for some reason has been passivated during the immersion testing, calls for further investigation. Nevertheless, the system passes the requirements to rust creep according to ISO 20340. The pull off values all meet the requirements to ≥ 2 MPa after exposure and ≥ 5 MPa before exposure.

System #	Panel #	System code	Blistering	Rust	Rust creep (mm)	Pull off value (MPa)	Mode of failure	Comments
1	1- IMS -1 1- IMS -2	SF_EP1	0(S0)	Ri0	0	8,7	Ad. Glue/topcoat	
			0(S0)	Ri0	0,2	8,7	Ad. glue/topcoat	Spots
2	2- IMS -1 2- IMS -2	SF_EP2	0(S0)	Ri0	0,1	9,7	Ad. to substrate	Spots
			0(S0)	Ri0	0,6	9,4	Ad. to substrate	Spots
3	3- IMS -1 3- IMS -2	FBE3	0(S0)	Ri0	0,1	7,5	90% co. top; 10% ad. glue/top	
			0(S0)	Ri0	5,3	6,9	Ad. Glue/topcoat	
4	4- IMS -1 4- IMS -2	FBE4	0(S0)	Ri0	0	13,0	15% co. top; 85% ad. FBE/PUR	
			0(S0)	Ri0	0,1	13,3	17% co. in top; 83% ad. FBE/top	
5	5- IMS -1 5- IMS -2	FBE5	0(S0)	Ri0	0,1	6,2	Ad. Glue/topcoat	
			0(S0)	Ri0	0,3	4,7	Ad. Glue/topcoat	
6	6- IMS -1 6- IMS -2	GF6	0(S0)	Ri0	0,8	8,3	50% co.; 50% ad. to substrate	
			0(S0)	Ri0	0,2	8,3	50% co.; 50% ad. to substrate	
7	7- IMS -1 7- IMS -2	SF_EP7	0(S0)	Ri0	0	11,6	Ad. to substrate	Spots
			0(S0)	Ri0	0	16,2	Ad. to substrate	Spots
8	8- IMS -1 8- IMS -2	STD_EP8	0(S0)	Ri0	0,1	11,0	30% co. top; 70% ad. glue/top	
			0(S0)	Ri0	0	11,9	40% ad. 2/3 coat; 60% ad. glue/top	
9	9-IMS-1 9-IMS-2	SF_EP9	0(S0)	Ri0	0	12,4	60% ad. subst.; 40% ad. glue/top	Spots
			0(S0)	Ri0	0,4	11,7	Ad. to substrate	Spots
10	10-IMS-2 10-IMS-3	SF_EP10	0(S0)	Ri0	0,3	10,3	50% co.; 50% ad. Substrate	
			0(S0)	Ri0	1,2	8,2	10% co.; 90% ad. Substrate	
11	11-IMS-1 11-IMS-2	FBE11	0(S0)	Ri0	4,9	9,1	Ad. glue/topcoat	
			0(S0)	Ri0	3,9	10,8	Ad. glue/topcoat	
12	12-IMS-1 12-IMS-2	FBE12	0(S0)	Ri0	1,8	9,8	Ad. glue/topcoat	
			0(S0)	Ri0	0	10,3	Ad. glue/topcoat	
13	13- IMS -1 13- IMS -2	FBE_Zinc 13	0(S0)	Ri0	1,4	5,8	Ad. glue/topcoat	
			0(S0)	Ri0	1,0	4,7	Ad. glue/topcoat	
14	14- IMS -1 14- IMS -2	GF14	0(S0)	Ri0	0,3	4,8	Co. in Glass flake	
			0(S0)	Ri0	0,1	5,4	Co. in Glass flake	
15	15- IMS -1 15- IMS -2	FBE5	0(S0)	Ri0	1,1	13,6	20% co. top; 80% ad. FBE/PU	
			0(S0)	Ri0	1,8	10,9	60% co. top; 40% ad. FBE/PU	

Figure 33 Results from Immersion test.

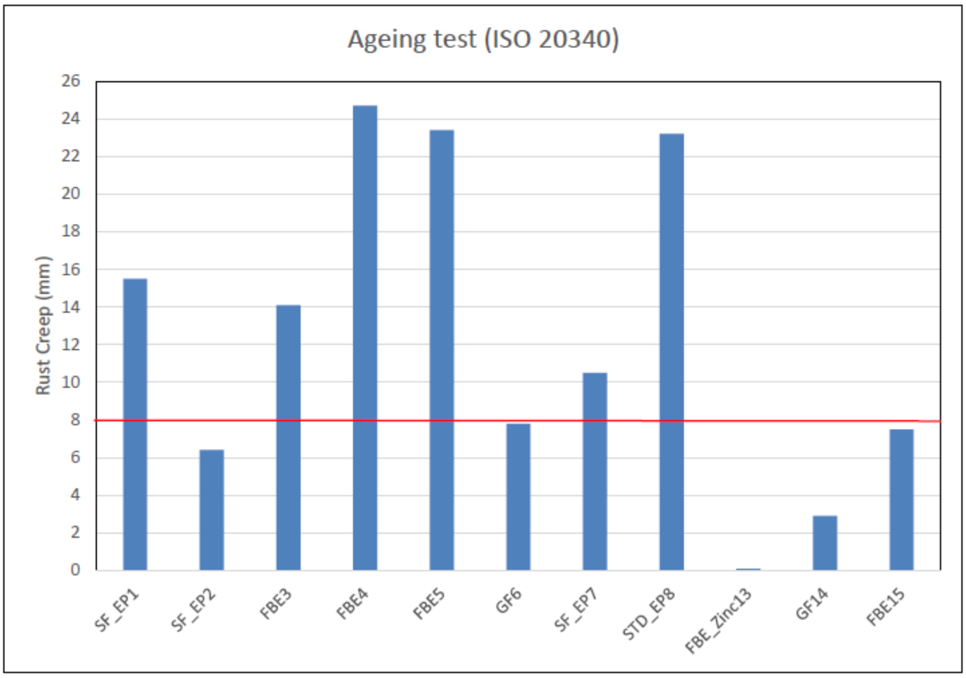


Figure 34 Rust creep measured from scribe, Ageing Test

In ageing testing, 45 % of all systems pass the ISO 20340 requirements. For SF wet epoxies, glass flake polyesters and FBE systems all candidates pass the test. There is a strong indication that zinc primer improves rust creep resistance (system 13).

In cathodic disbondment, testing 12 systems pass the ISO 20340 requirements = < 20 mm and 3 systems show a disbondment > 20 mm. The 3 systems failing the cathodic disbondment test are all FBE systems.

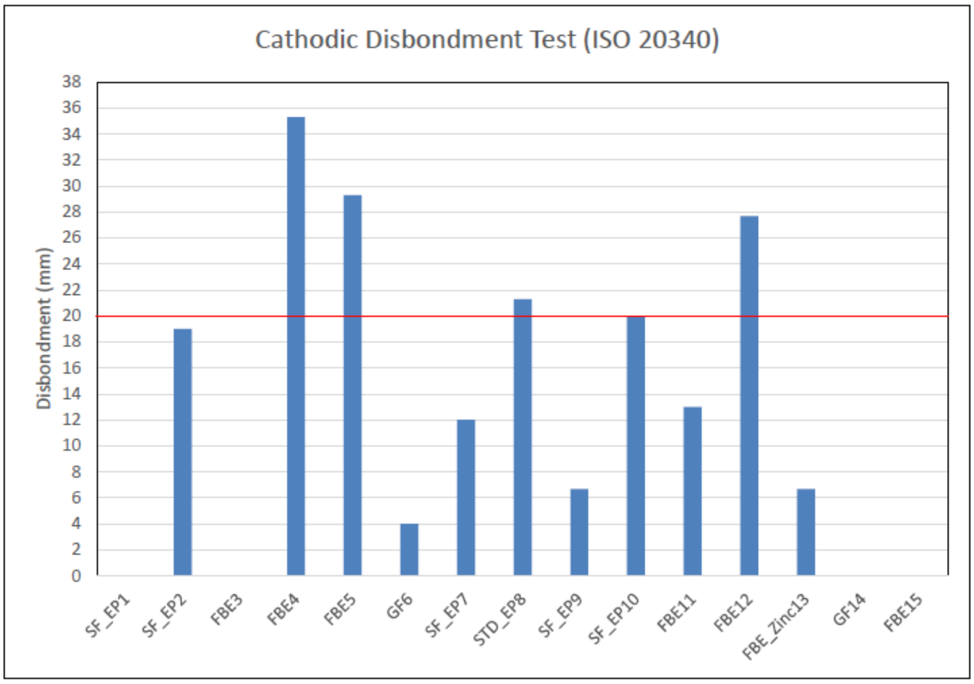


Figure 35 Cathodic Disbondment

Conclusion on coating systems

The aim of the activity was to compare conventional coating systems based on wet paint technology with fusion bonded epoxy technology with special attention to the application in offshore environment. ISO 20340 and parts of NACE TM 0404 have been used to evaluate the performance of the selected coating systems.

This evaluation is considered a screening of technologies and the procedures of the test standards have not been strictly followed. In that respect it should be noted that in general, the DFT's do not strictly meet the requirements of ISO 20340. Nevertheless, the testing has provided very valuable information and confirmed that useful candidates for offshore application may be found among all the tested coating technologies. Due to a limited number of test panels with acceptable DFTs, it was decided to present the data as the average value of the evaluated panels, typically 2 or 3 samples. The detailed overview of the single panel results may be found in Appendix F (Hempel raw data).

Mechanical testing (NACE TM 0404)

All coating systems meet the requirements for adhesion strength.

The FBE systems generally performed better in the impact test than the wet epoxy and the glass flake systems. Exceptions were the wet epoxy systems top coated with a polyurethane, which showed performance on par with the FBE systems.

In general, no cracks were observed on any system in the thermal cycling test except the glass flake systems. In this respect, it should be noted that cracks were only detected in the corner and due to the difficult geometry of the panels (L-shape) and difficulties during the spray application, excessive DFT was found in the critical areas. In addition to this, one of the glass flake systems (system 14) was in black color making evaluation for cracks very difficult. Therefore, FORCE Technology recommends TCT be redone on the two glass flake systems with correct DFT distribution and both coating types in light shade.

In general, the wet epoxy and the FBE systems showed expected flexibility of about 2 %. One exception was system 3 (FBE) with a very high elongation, >8%. The glass flake systems showed a slightly lower flexibility (< 1 %).

Exposure testing (ISO 20340)

All systems pass the immersion test showing no blistering and no rust, and the rust creep from the scribe is well below 8 mm (3 mm for zinc primed systems). An unusual behavior of FBE_Zinc13 was observed already during the 3 months' evaluation: A heavy build-up of corrosion products is observed around the scribe, despite the fact that no rust creep is detected. So far, no explanation for this phenomenon has been found.

In ageing testing approximately, half of the systems pass the ISO 20340 requirements. There is a strong indication, that zinc primer improves rust creep resistance (system 13). In cathodic disbondment testing 12 systems pass the ISO 20340 requirements (= < 20 mm) and 3 systems show a disbondment > 20 mm. The 3 systems failing the cathodic disbondment test are all FBE systems. Summary of the coating system performance (based on average values):

- Systems 2, 9, 10, 11, 13 and 15 "pass" the requirements for both ISO 20340 and NACE TM 0404. (However, system 10 only with limited performance in CBT).
- Systems 6 and 14 "pass" the requirements for both ISO 20340 and NACE TM 0404, but due to high variations in the applied DFT of the glass flake polyesters, we recommend not considering the results from NACE TM 0404.
- Systems 1, 3, 4, 5, 7, 8 and 12 "fail" the requirements for ISO 20340 (aging and/or cathodic disbondment).

Figure 36 Example of test plate after paint removal

PROJECT MANAGEMENT AND DISSEMINATION

Project management was divided between Siemens Gamesa (SGRE) as technical project lead and Offshoreenergy.dk (OEDK) as administrative project lead. SGRE was responsible for the progression of the project regarding technical development and the production phases, in cooperation with WP leaders. OEDK was responsible for project economy, financial disbursement, reporting, project documents and general guidance on EUDP rules and possibilities to the project partners. This cooperation was implemented and adjusted at previous EUDP projects (64015-0042 and 64014-0537) and carry general project management satisfaction from all partners. Because of this cooperation, the project partners are able to focus on their core competences, technical development.

On average, the project group had coordinating meetings every 3 month, not including internal meetings and focused sessions for project development.

Dissemination

Here is a list of articles about the project and results. Active links have been added to the headlines.

- Energy Innovation Cluster Yearbook 2017: (page 50)
- Altinget: Task force udvikler standarder for jacket-fundamenter
- Simulering af spændinger i k-knuder og fuldskala forsøg
- Byg-selv i stor skala: Vindmøller med 16 ton tunge samleled
- Lavere omkostninger i produktionen af vindmøllefundamenter skal give billigere grøn el.

On a more scientific level, the following publication have reached the public during the project:

- Mikkel L. Larsen, 2018, ”Simulering af spændinger i K-knuder og fuldskala forsøg”, Magasinet Svejsning 3. Juni 2018, pp. 12-15.

- Eric Putnam, 2018, ”Faciliteter til mekaniske tests af offshore komponenter på Lindø”, Magasinet Svejsning 3. Juni 2018, pp. 16-17.

- Mikkel L. Larsen, Vikas Arora, Marie Lützen, Ronnie R. Pedersen, 2017, ”Validation and model updating of weld in finite element model of K-node structure using experimental data for fatigue analysis”, 30th Nordic Seminar on Computational Mechanics (NSCM-30), pp. 109-112.

- Mikkel L. Larsen, Vikas Arora, Marie Lützen, Ronnie R. Pedersen, Eric Putnam, 2019, ”Use of 3D scan of weld joint in finite element analysis and stochastic analysis of hot-spot stresses in tubular joint for fatigue life estimation”, 38th International Conference on Ocean, Offshore & Artic Engineering.

- Mikkel L. Larsen, Vikas Arora, Marie Lützen, Ronnie R. Pedersen, Eric Putnam, 2019, ” Validation and model updating of weld in finite element model of K-node structure using experimental data for fatigue analysis”, 7th International Conference on Marine structures.

1.6 Utilization of project results

The study, production and testing of the node was an important step towards driving down costs for jacket foundations, thereby reducing the price of wind energy. The project was primarily initiated on the initiative of Siemens Gamesa's plans to develop their concept for jacket foundations and make the technology more competitive. Developments have already required enormous amounts of R&D and testing of the node was one of the last steps before Siemens Gamesa, together with a number of other partners, could take the big step and test and demonstrate a full-scale concept with modular suction buckets, modular jackets, new transition piece of concrete, new cable connection and a new, large wind turbine in an extensive H2020 project.

The project generated important deliveries such as corrosion analysis, market analysis for the ability for robot-based nodes and production and testing of the nodes

All deliveries play an important role in the commercialization of the concept. Especially corrosion test and test of the nodes have contributed with new, important knowledge.

Several of the project's results are already being used in another project, CeJacket, which is about developing more efficient methods of producing jackets. The goal is also to reduce the cost of jackets. In addition, the results from the node project are transferred to i4Offshore.

The project partners have all had commercial interests in the project. Siemens Gamesa is interested in reducing the costs of wind turbine foundations, but FORCE Technology and Bladt have also participated in the project to develop their own business.

FORCE technology is not in direct contact with the supply chain for nodes for jackets or jacket production. They contribute to the value chain through technology development and validation. FORCE has seen added growth as an effect of the NODE-project and participated in the necessary technological development and validation activities that were related to the development of the NODE concept. The growth includes mechanical test on small and large scale, laser hybrid welding, and corrosion and metallurgical tests and studies.

FORCE has launched a new business area for mechanical testing on a large scale and matured their business area in laser hybrid welding through the NODE project. These two business areas already show positive turnover and have significant expected growth, as shown in the expected turnover over the next 3 to 5 years.

Bladt Industries was part of the project, for example, to examine the possibilities of a robot-welded node, but also to optimize the manual production of the node. At present, foreign labor will be in sharp competition to any Danish producer, but in full automated production of nodes, Danish suppliers will be proficient and especially competitive on quality, as the test of the nodes has proved to be essential.

Bladt does not expect to immediately see the great impact of the project before their newly purchased welding robot will be able to weld nodes of this size. If this will be a success, they will not only be able to keep jobs in Denmark, but they will also see expand in the production. Compared with manual production of nodes, Bladt could reduce the production time by 50 to 75% with a well-functioning welding robot.

For Bladt Industries, participation in the project has led to great industrial interest and participation in two further development projects to produce nodes. The project's results have undoubtedly made it easier to penetrate the market, but the commercial potentials certainly depend on the results from CeJacket and i4Offshore.

Crucial for the commercial aspects of the project is that the results are embedded in subsequent development projects. This has been done in the form of the projects CeJacket and i4Offshore, which are also aiming at optimizing the production of jacket foundations to reduce costs on wind energy. The node project has formed a crucial basis for further development.

The development of more cost-effective production methods and the full-scale installation of the overall concept will put the last pieces in the puzzle in this instance and by success, it is very likely that this type of foundations will be used in areas where the water depth is too large for monopiles. This considerably increases the number of potential offshore wind farms and opens the possibility of more wind energy in our electricity system.

The project has, among other things, shown that with the correct production method, one can produce nodes in this way, and the test showed that this type of welding can last for the lifetime and more. The analysis of the node also showed that the crack does not necessarily start in the welding toe but is initiated by differences in the geometry of the weld (for example, seen on the third node). This is important knowledge to reduce the risk of cracking throughout the life of the node and proves a need to test possible solutions, e.g. to grind the weld.

Generally, it will take some time before the real effects of the project can be measured. Siemens Gamesa will see an effect if the newly developed concept leads them to win orders for wind turbines that are adapted to the new jacket foundation. If orders are won, the effect can be measured throughout the value chain and have a great impact on the Danish industry.

There has generally been great interest in the project from the industry. Ørsted was not originally part of the project but saw a great potential for this type of jacket foundations and later, they became part of WP4 and brought to the project production, test of analysis of a third node. Thus, approx. 4 million DKK for the project through Ørsted's own payment of the last test.

For FORCE Technology the results of the project related to LHW technology are of paramount importance. The results provide a basis for the future service of the industry related to welding of heavy metal structures. It will maintain FORCE Technology as one of the world leading partners on the market in the area of LHW technology.

For Siemens and Bladt Industries new perspectives for joining large steel constructions as NODE’s, more productively, have aroused. It is now only a matter of when the LHW technology will be introduced to this industry – who will take the first step – and pick up the gain.

1.7 Project conclusion and perspective

As described above, the node project is an important piece of a larger puzzle to develop a new, cost-effective concept for jacket foundations. The project has contributed with important knowledge regarding the production of nodes and surface treatment of foundations. Data and knowledge produced in the project will be used in the two projects mentioned, CeJacket and i4Offshore.

Based on the results of the laser hybrid welding, it is not necessarily expected that this type of production will be used for node production within 5 years. On the other hand, we will surely see that the node project will lead to adoption within other large steel constructions for e.g. onshore and offshore wind.

The project has shown great potential for more efficient production, but also helped identify areas where R&D is still needed to be able to commercialize the concept.

Several Danish companies have already invested in welding robots, but most now focus on welding long-length and not complicated circular seams. It was not possible in this project to produce a not using robot welding, which is an expression of necessary development in that area. Bladt has subsequently invested in a welding robot, which has the potential to weld these complex structures automatically and in sufficient quality with, among other things, grinding, over-hammering and peening.

Annex

WP 2

1 Welding results – node and flange

WP 3

2 Manufacturing drawing - assembly

3 Bladt final report

WP 4

4 Coating system for SGRE offshore jacket design

5 Final report full-scale test

6 K-node Test History and Results presentation

7 Finite Element Modelling presentation

8 FORCE K-node Test Program