THERMOPLASTIC COMPOSITE PIPE; OPERATIONAL EXPERIENCE IN DEEPWATER AND TECHNOLOGY QUALIFICATION

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ABSTRACT

Airborne Oil & Gas (AOG) is the world’s first and leading manufacturer of fully bonded, Thermoplastic Composite Pipe (TCP). The unique continuous manufacturing process produces a fully bonded solid wall pipe with glass or carbon fibre reinforcements completely embedded within the thermoplastic material. This lightweight, flexible composite pipe is enabling for deeper water exploration, production and intervention, and puts an end to corrosion and oil spills. In November 2012, AOG delivered a TCP Downline to its client Saipem SA, to be used for the pre-commissioning of several pipelines in the Guara & Lula field in Brazil, at 2140 meter water depth. Through 2013 and 2014, the client completed four pipeline pre-commissioning campaigns with the TCP Downline. The paper discusses the specific benefits of TCP that lead to the selection of this technology for this project. It discusses the design of the TCP Downline for this application, the initial qualification program and the operational experience with the pipe in the field. The many deployments that have been successfully completed with the pipe provided a wealth of operational experience and knowledge. In between campaigns two and three and after the last campaign, sections of pipe have been inspected, and subjected to a specific and extensive testing program. By comparing the residual life test results with the usage during the operations, the loading history and the validated condition of the pipe, the design is validated and the suitability of the TCP Downline for future use was confirmed. The results of this work have been the basis for further development and qualification of the technology for other oilfield applications.

1 INTRODUCTION

In November 2012, Airborne Oil & Gas delivered a TCP Downline and reeler to Saipem SA, to be used for the pipeline pre-commissioning of two gas export pipelines in the Guara & Lula field in Brazil. Installed at 2140 meter water depth, the pre-commissioning activities needed to be conducted at this water depth. For the campaigns, Saipem chose an approach whereby the hydrotesting and de-watering activities would be conducted from the surface, using an Airborne thermoplastic composite pipe (TCP) to connect to the pig launcher. Saipem selected the Airborne TCP Downline for this job, because of its unique characteristics; the spoolable TCP combines a smooth bore with collapse resistance and low weight, allowing the use of a horizontal lay system instead of a large and expensive vertical lay system. With the type of operation requiring a high safety class, an extensive qualification program was conducted on sections of the pipe prior to delivery.

Through 2013 and 2014, the client completed four pipeline pre-commissioning campaigns with the TCP downline. These campaigns included more than 45 deployments to over 2100m water depth, as well as over 150 days in fully deployed mode, suspended from the side of the vessel. After two campaigns, before the third campaign, the residual life of the TCP was assessed to evaluate further usage of the system. Again at the end of its life, after 4 campaigns, another evaluation was done. This was one of the first detailed evaluations of a composite flexible pipe riser system that had been designed for and used in deepwater in a challenging dynamic application. Thus it provided a wealth of operational experience and knowledge as well as used conditions of the pipe in this extreme environment.

First this paper outlines the basic Thermoplastic Composite Pipe concept as well as the system as deployed by client; the design is described alongside critical combined load cases and long term effects. The validation of the design through rigorous testing is briefly outlined. The operation is discussed with the expected life consumption, followed by the assessment of residual life on sections that returned from the field. Then, the original design is checked against life consumption and residual life, leading to the conclusions. At the end also an insight is given on the current state of technology and qualification approach for this TCP product.

2 SYSTEM OVERVIEW

Airborne Oil & Gas developed the Thermoplastic Composite Pipe concept (TCP), indicated in Figure 1. The TCP has a solid wall construction made-up from a single polymer material and embedded (melt-fused) fibre reinforcements. The solid wall consists of an inner liner, thermoplastic composite reinforcement layer and an outer coating. All layers are of the same thermoplastic polymer and are fused together during the production process to form a solid, fully bonded laminate.

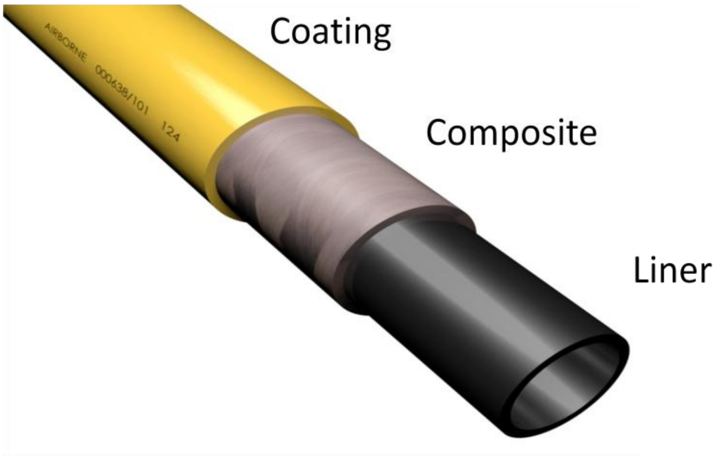


Figure 1: Airborne’s Thermoplastic Composite Pipe concept

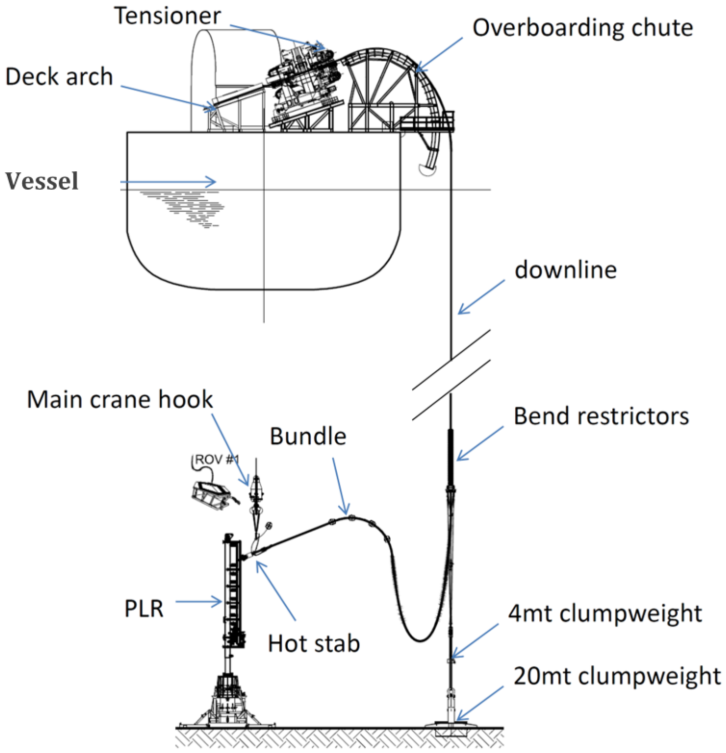


Figure 2: Deployment configuration

The fully bonded TCP has advantages that are particularly beneficial when the pipe is used as a fluid conduit (downline, annulus hose, circulation line, etc) for access to a well or pig launcher in deepwater work-over, intervention and pre-commissioning applications; the TCP Downline is spoolable, has a smooth bore featuring low pressure drop, is collapse resistant to large water depth and combines pressure and tensile strengths with spoolability. The low weight of the TCP Downline is a benefit in general, but also requires specific attention for the operation: a lightweight pipe inherently has a low terminal velocity and is more susceptible to currents, which places specific requirements on the configuration in which the TCP Downline is deployed. The client applied the configuration as indicated in figure 2, consisting of the following elements:

- The TCP Downline. Connected on the vessel to the reeler, run overboard over an overboarding chute, down to a position close to the seabed. The subsea end-fitting is fitted with a mounting plate for the bend restrictor elements and a lifting collar. The TCP Downline is 3 inch ID, rated for 5000 psi internal pressure (345 bar), 250 bar external pressure and 20 metric tons of tensile load.
- A bend restrictor, avoiding that the downline would over bent at the seabed end. Bending plus external pressure being an important combined load case for the downline, the bend restrictors avoid overloading of the downline at this point.
- A dynamic clump weight. This clump weight was connected to the subsea end of the TCP Downline, and run overboard with the downline to the seabed. The size of the weight, in the form of steel chains, was adjusted to suit the dynamic requirements for the system. This depended, amongst others, on the medium to be pumped (i.e. fluid or gas).
- A static clump weight, or dead man anchor, placed on the seabed. This dead man anchor prevented too large loads to be transferred to the pig launcher. The connection between the subsea end-fitting of the downline and the dead man anchor was established by means of 4 slings, including a weak link to avoid damage in case of vessel drift off.

- Hose bundle, connecting the downline to the pig launcher. The hose bundle consists of multiple small high collapse resistant (HCR) hoses, and take up the heave of the vessel. The hose bundle is fitted with a hot stab and crane hook.
- Pig launcher. The pig launcher is connected to the pipeline and has multiple access points for the hot stab.

The lightweight TCP Downline allows for a horizontal lay spread to be deployed, reducing the cost significantly. The system used is indicated in Figure 3 and consists of the following main elements:

1. Reeler. A constant tension reeler with integrated powerpack. Featuring a fully enclosed frame and swivel, the reeler protects the TCP Downline. The constant tension allows the reeler to follow the tensioner during deployment.
2. Deck arch, or deflector. To best utilize the deck space behind the spread for the pumping equipment, Saipem applied a deck arch, or deflector.
3. Tensioner. A standard small 60 tons tensioner is used to run the downline and keep it in place during the operation.
4. Overboarding chute. Designed with an exit curvature to mitigate fatigue issues, the overboarding chute plays a vital role in the total spread.

Figure 3: Deployment spread

3 PIPE DESIGN & QUALIFICATION TESTING

The design methodology was based on *The Project Guideline for Bonded Flexible Thermoplastic Composite Pipe for Offshore Applications* [1], DNV OS-C501 *Composite components* [2], and DNV RP-A203 *Recommended practice for qualification procedures for new technology* [3]. The design methodology follows the DNV OS-C501 format of 'Load and Resistance Factor' design. At the moment this Guideline is being transformed into a standard by a Joint Industry Program (JIP) lead by DNV GL, this will be shortly discussed at the end of this paper.

A Failure Mode Effect and Criticality Analysis (FMECA) is an essential part of the design method. All functional requirements and all related failure modes are listed. Burst or excessive deformation are two examples of failure modes. In general, functional requirements and failure modes are defined at system level. However, the occurrence of a failure mode is a result of failure at a much lower level, namely at material scale.

Failure at material scale occurs due to a limited number of failure mechanisms. For a TCP these failure mechanisms are for instance fibre failure, matrix failure or delamination. The resistance (strength) of each failure mechanism has been determined by material (coupon) testing. For thermoplastic composites, the resistance is in general not constant, but depends on time (such as fatigue load cycles, or creep), temperature and environment (fluids).

The relation between loads acting on the TCP and stresses has been established by performing Finite Element (FE) simulations. The FE model utilizes an accurate material model that has been validated by all coupon test results.

Once the resistance of each failure mechanism and the magnitude and duration of the loads is known, the probability of failure can be accurately assessed in the FMECA.

Based on the FMECA results, a qualification program was established. An overview of the qualification tests can be found in Table 1. The qualification testing includes characterization tests (stiffness), short term static tests, long term static tests (creep and stress rupture), fatigue tests and tests on repaired samples and samples exposed to environment. Acceptance criteria for each test are based on predicted (calculated) TCP performance. If the test results are in line with the prediction, the design tools are validated.

The measured stiffness was found to be in close agreement with the predictions. For the static test results, a comparison between predicted and measured strength is given in Table 2. Again, predictions are found to be in close agreement with tests.

The long term static qualification tests were performed to validate the long term resistance of two relevant failure mechanisms. For long term tensile loads, the critical failure mechanism is fibre tensile failure (stress rupture) and for long term compressive loads, the critical failure mechanism is local fibre buckling. Fibre buckling resistance depends linearly on the creep modulus of the composite matrix material and hence reduces over time when the TCP is subjected to a long term compressive load, such as bending or external pressure. For both stress rupture and fibre buckling (creep), the design codes [1,2] state that Miner’s rule shall be applied to evaluate the effect of successive long term loads. For stress rupture, this is logical, since the long term load induces small damages in the fibre at micro-scale which do not disappear when the load is removed. However, for fibre buckling application of Miner’s rule is disputable, since the reduction of stiffness is merely a visco-elastic effect which is reversible. In order to be conservative and to follow the design codes, Miner’s rule has been applied for both stress rupture and creep during the design of the TCP. An overview of predicted and measured long term bending performance of the TCP is indicated in Figure 4. Similar to the short term static tests, the TCP behaviour is accurately predicted and experimental results are very consistent. Also the long term internal and external pressure performance of the TCP was in close agreement with predictions.

From a design point of view, the most critical long term load is storage on the reel, especially at elevated temperatures. Therefore storage pressure was applied during long term storage on the reel and the amount of consumed creep life was monitored by measuring temperature, storage pressure and storage duration. Notice that this load case was critical due to the fact that according to the DNV standard Miner’s rule had to be applied, i.e. the effect successive storage periods had to be added. Based on these test results, discussions with DNV will be initiated in order to reflect the reversible nature of creep in the design code.

The fatigue qualification tests were performed to validate the fatigue resistance of the relevant failure mechanisms: fibre tensile failure. In addition, an axial fatigue survival test on a TCP with end-fittings was performed to address potential secondary effects due to the end-fitting. In this survival test the TCP was subjected to a tensile fatigue load twice as high as the actual tension fatigue load up to the total number of expected fatigue cycles during operation. After fatigue testing the sample was loaded up to 900kN (limit of test equipment) without failure.

From a design point of view the most critical fatigue load is reeling/unreeling. Bending and tension fatigue on the overboarding chute was found to be less critical, since the radius of the overboarding chute is larger than the radius of the reel (storage MBR). The reeling/unreeling case is included in the qualification test program by bending the TCP to the storage MBR while it is pressurized at design working pressure. The adopted fatigue life calculation methodology is based on normalized Goodman diagrams of the composite material and application of Miner’s rule. By using normalized Goodman diagrams, the effect of static strength on the fatigue performance can be incorporated. The fatigue life is predicted for two cases: based on the average virgin material strength and based on the Lower Confidence Limit (LCL) of the virgin material strength. The LCL is based on the mean strength and the measured standard deviation. All design calculations are based on the LCL strength.

The actual fatigue life is expected to be within the predicted range, but closer to the value based on the average virgin material strength. A comparison between predicted and measured fatigue life for reeling/unreeling is listed in Table 3. The measured scatter in fatigue life of the TCP is extremely low. This could be incidental because only two samples have been tested; however as this low scatter is observed in most of the testing, it could be an interesting feature of the TCP that would require more testing to be confirmed.

Obviously, the design calculations include detailed investigations on the behaviour of the TCP in the tensioner, effect of handling loads etc. Also accidental loads and possible overloading scenario’s that have been addressed during FMECA sessions were evaluated during the design phase.

As mentioned before, the resistance (strength) of each failure mechanism depends on time (or number of fatigue cycles), temperature and environment. Based on available material test data and knowledge of expected service conditions, a strength reduction of 12.5% was estimated for fibre dominated failure during the intended operations and the reduction has been incorporated in all design calculations. For matrix dominated failure, no reduction is expected given the tough behaviour of the thermoplastic matrix material (measured fracture toughness for glass-PP is 2.5 kJ/m^2, whereas for carbon-epoxy the fracture toughness is typically 0.4 - 0.8 kJ/m^2) and the fact that the loads are mainly carried by the fibres. However, in order to be conservative, a reduction of 12.5% for matrix failure is included in the design calculations. In addition, the expected strength reduction enables prediction of residual TCP performance after completion of the two offshore campaigns.

Based on the qualification test results it is concluded that the TCP behaviour is very predictable and consistent. Especially the predictability is an important aspect for acceptance of new technology.

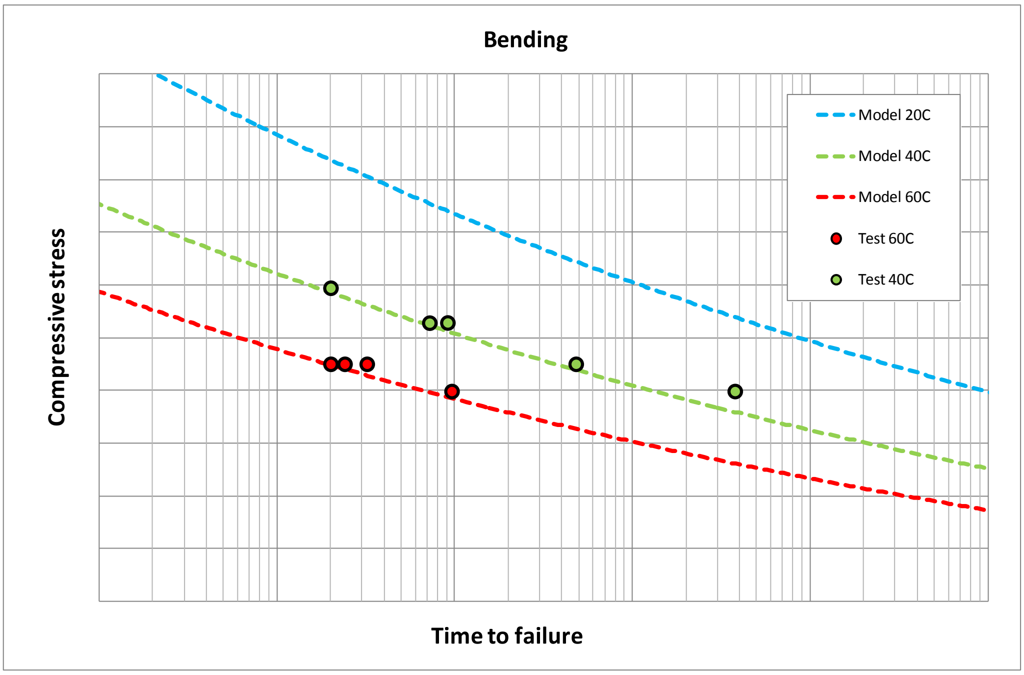


Figure 1: Predicted and measured long term bending performance of TCP

Test	T (°C)	Nr. of samples	Additional specifications
Characterization			
Axial stiffness	RT	3	Combined with axial tension test
Bending Stiffness	RT	1	Stiffness determination and up to the MBR of 3.36m .
Torsional Stiffness	RT	2	Up to 5000 Nm, stiffness determination.
RGD	65	10	Determine resistance against RGD.
Static tests			
Short-term IP	RT	3	Up to failure.
Short-term EP	RT, 60	3	Up to failure.
Axial Tension	RT, 60	3	Up to 900 kN, determine axial stiffness.
Axial Compression	RT, 60	5	Up to failure.
Plate Crushing	RT, 60	5	Up to failure.
Long term testing			
Long-term IP	60	3	Survival test + residual IP.
Long-term EP	RT, 60	12	Regression testing
Long-term Static Bending	40, 60	12	Regression testing
Fatigue			
Axial Tension Fatigue	RT	1	Survival test. 50-150 kN, 1E6 cycles.
Bending Fatigue	60	2	Up to failure. Straight to storage MBR, with IP
Fluids and Repair			
IP after exposure	RT	1	Up to failure.
Axial Tension after exposure	60	1	Up to 900 kN.
Long-term EP repaired samples	60	2	Survival test

Table 1: Overview of qualification tests

Load Case	Temperature	Calculated	Test result
Internal pressure	RT	1514 bar	1534 bar
External pressure	RT	743 bar	> 700 bar*
External pressure	60 °C	565 bar	580 bar
Axial tension	RT	1465 kN	> 900 kN*
Axial tension	60 °C	1445 kN	> 900 kN*
Axial compression	RT	850 kN	910 kN
Axial compression	60 °C	648 kN	705 kN
Plate crushing	RT	240 kN/m	275 kN/m
Plate crushing	60 °C	160 kN/m	225 kN/m

* Limit of test equipment

Table 2: Overview of predicted and measured static failure loads

Cycles to failure		
Calculated Mean virgin strength	**Calculated LCL virgin strength**	**Test results**
48400	17000	36154 36179

Table 3: Comparison of predicted and measured fatigue life

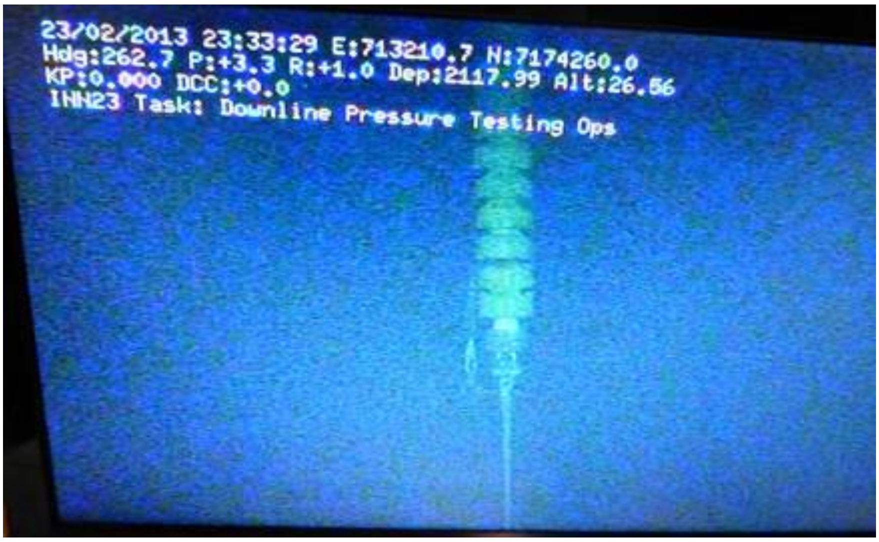
Cycles to failure		
Calculated Mean residual strength	**Calculated LCL residual strength**	**Test results**
11300	2640	11231 10521

Table 4: Comparison of predicted and measured residual fatigue life

4 OPERATION

Through 2013-2014, the TCP Downline completed three pipeline pre-commissioning campaigns for Saipem. These campaigns included more than 45 deployments to over 2100 meter water depth, as well as over 150 days in fully deployed mode. Figure 5 shows the first ever footage of a composite pipe in this water depth. During the campaigns, all phases of each operation were carefully monitored by Saipem. The monitoring included, amongst other things, the pressure, tension at the tensioner, number of cycles, conduit content, and temperature. This was done for all phases of the operation, including storage, deployment, operation and recovery. With this data, a good overview was available of the loading history on the TCP Downline. During these operations, the TCP Downline was subjected to all relevant long term effects and loading such as combined load cases, dynamic loading, fatigue loading, long term internal pressure, external pressure and creep. It once happened that the weak link at the slings, connecting the subsea end of the downline to the Dead Man Anchor, released as result of overloading after which the downline was recovered without being damaged.

During these operations, various levels of damage occurred on the TCP Downline. These range from scratching to more severe coating damage, which was likely to be caused by the use of standard tensioner pads. During one of the campaigns also one tensioner pad was actually missing. Where the scratches required no repair, the coating damage was repaired on two distinct locations alongside the downline. These repairs were executed offshore onboard of the vessel (indicated in Figure 6). For future campaigns the tensioner pads will be adjusted to ensure proper load transfer from the tensioner to the load-carrying laminate of the pipe.



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KP:0.000 DCC:+0.0
INH23 Task: Downline Pressure Testing Ops
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Figure 5. TCP Downline first deepwater deployment

Figure 6: Coating repair after tensioner malfunction

5 RESIDUAL LIFE TESTING AND DESIGN VALIDATION FOR LIFE EXTENSION AND OPERATION

The residual life test program was done after two campaigns for a life extension program (originally the TCP was designed for just two campaigns by client). The program consists of three main parts:

1. Determination of residual static strength
2. Determination of residual creep life
3. Determination of residual fatigue life

Static strength reduction is measured by performing an internal pressure burst test and by measuring the residual delamination strength. The residual burst pressure was measured to be 1344 bar, i.e. a reduction of 12.4% with respect to the virgin value. As mentioned before, the accounted reduction was 12.5%. Thus, the strength reduction is predicted very accurately. For the residual delamination strength no reduction was measured compared to the virgin performance.

The residual creep life is measured by long term bending tests at elevated temperature. Two samples from the top-side, which have seen most long term bending load since they are located on the reel drum during storage, have been tested. The measured residual creep life was more than twice as long as the virgin time to failure. This confirms that creep is reversible and that therefore application of Miner’s rule is too conservative. The fact that the residual life is even longer as the original life can be explained by the fact that the virgin TCP contains residual thermal stresses from manufacturing and these stresses reduce over time due to relaxation of the thermoplastic material. Based on the test results it is concluded that the residual creep life is equal to the virgin creep life.

Residual fatigue life is measured by performing the same reeling/unreeling test as done for virgin samples. When the predicted reduction of static strength (-12.5%) is included in the fatigue calculations, the predicted residual fatigue life equals 11300 cycles (based on mean reduced strength) and 2640 cycles (based on LCL reduced strength). The measured number of cycles to failure was 11231 and 10521, see Table 5. Identical to the virgin case, the measured cycles to failure are close to the predicted cycles to failure based on mean reduced strength, instead of the LCL. Again, the scatter in test results is remarkably low, proving that the TCP behaviour is very consistent.

It has been shown that the residual fatigue life is accurately predicted by incorporating the reduction of static strength. Based on the evaluation a life extension was given, with a down-rating of the product for pressure and tension loading. This resulted in a third and fourth campaign being completed by client.

At the end of the fourth campaign the pipe was significantly damaged, which resulted in that the pipe was taken out of service , followed by a thorough investigation of the events leading up to the damage and a comprehensive evaluation resulted. One of the findings was that even with close monitoring, a number of load cases had not been accounted for in the design as they had not shown up in earlier evaluations. In particular, un-documented repetitive pressure tests (in between operations) had been executed accumulating to the overall consumed fatigue life , and that with load ratings, actual loads were sometimes still higher than the specified values. Another example of operational lessons learnt, that was discovered at later stage by simulations, is that the tension monitoring was done at a location, which had reduced tension due to friction, showing much lower loads than actually occurred on the pipe.

Overall, the evaluations after the damage provided a very good picture of the pipe performance in the field and valuable information for further product design and use.

6 THERMOPLASTIC COMPOSITE PIPE QUALIFICATION

As shown for the downline, current products are client specific qualified, where the qualification is based on existing codes, such as DNV OS-C501, API17J and the DNV GL TCP standard in development, and which are demonstrated to work well. Besides this, AOG is finalizing a generic qualification of the TCP according to DNV RP-A203, Technology Qualification,in preparation for standard qualifications with the new standard. This covers the qualification of individual generic technology packages, ie. the structural analysis tools (FE non-linear, fatigue, creep), the material characterizations, the standard production qualification (for type approval). With these in place a standard product qualification can be run under DNV RP-A203 or under the new standard.

The full qualification work is done under DNV GL. It is a systematic approach to the qualification of new technology, and thus a tool to prove that the technology functions within specific limits with an acceptable level of confidence. This will be completely similar to what was done in the downline, however all steps are verified and validated by DNV GL. This will constitute the basis to work from for all new products.

The material characterization is being performed for the current three baseline materials (GFPE, GFPP, GFPA12). The material test programs include

- Physical characterisation (thermal, density, UV resistance, etc.)
- Chemical compatibility (swelling, absorption/desorption, ageing, etc.)
- Static mechanical properties (shear, tension, compression, ILSS etc.) in critical conditions (wet, dry, cold and hot).
- Long term static mechanical properties (Creep, relaxation) in critical conditions (wet, dry, cold and hot).
- Dynamic (fatigue) material properties, in critical conditions (wet, dry, cold and hot)

The material tests are done on:

- Polymer coupons from the liner, coating and laminate polymer
- Laminate coupons in various lay-ups and geometries (UD, Quasi isotropic, 0/90, +-45)

The conditions taken are from the extremes of the applications. Temperatures cover the range from cold -20degC to hot 80degC, with reference tests at Room temperature. And for environment conditions the materials are soaked and tested in representative fluids like Norsok oil, seawater, or injection fluids, for example Methanol.

Material testing is done at professional test houses like Norner, Element, Dutch Aerospace Laboratory and WMC and all tests are witnessed by independent 3rd party. At the moment of writing, the GFPE and GFPP material characterization tests have been completed for over 80%, and only the longer running coupons of the long term tests are still running (ageing, creep & fatigue). The GFPA12 testing is at approximately 40% of completion.

The Airborne design methodology, design basis, approach, calculation methods have been evaluated. The calculation methods developed, have been shown and demonstrated by sensitivity analysis, example calculations and extensive test result verifications. The test result verification was done on the huge amount of data of past and current experience with all TCPs manufactured and tested by Airborne in the past 7.5 years. This includes full diameter ranges (from 1” ID to 9.5” OD), all baseline materials, varying thickness/diameter ratios (from 8 layer to 104 layer pipes) and all fibre lay-ups (strong and stiff design vs flexible designs). The tools, which were developed, are based upon 3D FE analysis (Abaqus), with detailed composite analysis, and including full material non-linearity for all polymers and composites. Models include both the TCP and the end-fitting, with detailed non-linear contact analysis of the interfaces. The tools also include the material specific developed fatigue and creep analysis.

For the production process, Airborne has written comprehensive reports, outlining the critical parameters for the quality of the product, the process procedure and the production procedures. This is part of the general quality assessment and has been approved as such by DNV GL. The quality of the production and the critical process parameters to quality have all been substantiated by over 7.5 years of experience with background documentation of process phases, from each product manufactured and by the production report of the delivered products. DNV GL is at the moment the only independent authority with access to Airborne production details, and has witnessed the production multiple times now.

With respect to the new standard by DNV GL, it is expected this will be finished Q3 2015. The work is sponsored by 19 industrial parties, of which 5 oil majors, 5 contractors, manufacturers and suppliers. Also with API a reservation was made within API17 to develop a Recommended Practice for Thermoplastic Composite Pipe. This activity is chaired by Airborne Oil & Gas and will follow up on the DNV GL standard.

7 CONCLUSIONS

This paper represents one of the first testimonies of the performance of a Thermoplastic Composite Pipe in the field. A TCP has been designed and qualified for the application of downline for pre-commissioning. It has been used in the field for over a year; it has seen over 45 deployments to 2100 meters water depth, and has been deployed for over 150 days.

Pipe sections that were returned from the field have been subjected to a residual life testing program. Through this testing, an assessment can be made of the validity of the design used for the TCP. With this, ultimately a conclusion can be drawn on the suitability of the TCP in this application and more wider in the offshore industry. The following conclusions can be drawn:

1. The residual life testing program has proven the validity of the design of the TCP for all loads, including short term loading and, more important still, long term loading.
2. The TCP Downline performed well in this application, with a small strength consumption due to the use in the field.
3. The TCP is proven in the application of downline for pre-commissioning in deep water.
4. The design method adopted is proven to be valid for the load cases that have been considered. For other applications, as long as the same load cases apply, the design method applies too.
5. From the field use, extensive learnings were achieved and implemented for future designs. Both in theoretical design approach as in practical offshore usage.

Applicability of Miner’s rule for creep will be further investigated and discussed with DNV. Furthermore, the low scatter observed in TCP testing will be evaluated in more detail.

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