# White Paper: Design & Qualification of Thermoplastic Composite Pipe

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# Abbreviations

| | |
|---|---|
| DNVGL | Det Norske Veritas Germanische Lloyds |
| EGF | E-glass fibre |
| LRFD | Load and Resistance Factor Design |
| PE | Poly Ethylene |
| PP | Poly Propylene |
| PA | Poly Amide |
| PVDF | Polyvinylidene fluoride |
| PEEK | Polyether ether ketone |
| RP | Recommended Practice |
| STD | Standard Deviation |
| TCP | Thermoplastic Composite Pipe |

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# 1 Introduction

As the first and leading manufacturer of Thermoplastic Composite Pipe (TCP), Airborne Oil & Gas has initiated and championed the creation of a dedicated standard for the use of TCP offshore and subsea. Late 2015, these efforts resulted in the issue of the recommended practice DNVGL-RP-F119 Thermoplastic Composite Pipes.

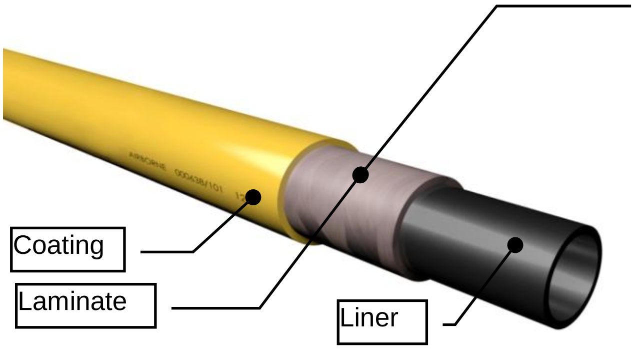
“Thermoplastic composite pipes are a new, robust lightweight pipe alternative that will impact field layout, installation methods and ultimately reduce cost levels”, says Per Anker Hassel, project manager with DNVGL – Oil & Gas. DNV GL led a joint industry project involving 18 companies covering the whole supply chain, including Airborne Oil & Gas.

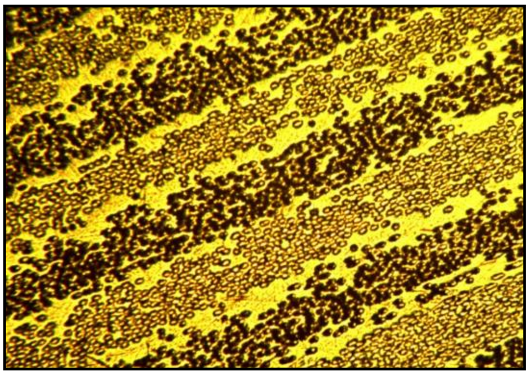
It is our goal to drive the adoption of the TCP across the industry and see more TCP deployed in the field. Therefore, where the recommended practice itself is a very comprehensive and large document, this white paper endeavours to create a more high-level overview of the design and qualification approach. This document can act as starting point for people who want to learn more about composite pipes in offshore applications, and is intended for engineers, Technical Authorities and managers active in the SURF, Subsea Intervention, Drilling and other related fields of activity.

We describe the fundamentals of the RP-F119, how to implement it into the design of a pipe system, and how to qualify. We explain the basics of a Thermoplastic Composite Pipe and its unique characteristics covered in the words ”thermoplastic” and “composite”. Finally, when basics are understood and interest raised, we can take things deeper with dedicated training. We recently received our first certificates from DNV covering the general design methodology for TCP, production and first material, enabling us to take you through the process step by step.

This document is written by Airborne Oil & Gas B.V.

## 2 Thermoplastic Composite Pipe Technology



The Thermoplastic Composite Pipe, or TCP, a concept originally developed by Airborne Oil & Gas in the mid 90’s, features a solid pipe wall constructed from glass or carbon reinforcement fibres and thermoplastic polymeric materials. The unique and proprietary melt-fusing manufacturing process results in a true composite pipe structure, with the fibres fully embedded within the polymer matrix and ensuring the strongest interface possible between the different pipe layers.

The TCP offers a unique combination of benefits for the user:

- High strength
- Low weight
- Spoolability
- No corrosion
- Superior fatigue performance
- High toughness and durability

The pipe design and materials are engineered to fit client demands. Glass and/or carbon fibres are used for reinforcement, and for example PE, PP, PA, PVDF & PEEK polymer materials for the liner, composite matrix and coating.

## 3 Recommended Practice Background

The RP-F119 describes a design based approach to the design and qualification of TCP. Where the RP issues requirements for the design and qualification of TCP for offshore applications, it builds on existing more generic standards dedicated to composite materials, such as DNVGL-OS-C501. It is intended for both suppliers of TCP products as well as operators and other users, to understand, design, qualify and ultimately successfully use the TCP products in their operations.

The RP builds on having a fundamental understanding of the design, materials and production of the TCP:

- Thorough understanding of the application, including all load cases, temperatures and fluids, both during installation and in service conditions
- Validated design methods, understanding and accurately predicting all the failure modes of the pipe and end-fittings
- Detailed material models based on material testing, showing the behaviour and strength of materials under influence of time, temperature and fluids

- Proven and robust production, capable of producing continuous length, repeatedly

By combining a solid basis on material level with the certified design method, the final product is qualified using a limited number of full-scale test; this way both time and cost are minimized.

# 4 Design Approach

## 4.1 Basics of composites

A composite material exists of fibres and polymers. The function of the fibres is to carry the loads and the function of the polymer is to keep the fibres together and transfer the loads to the fibres. In composite terminology, the polymer is called the 'matrix'.

The fibres are linear in behaviour and do typically not show plastic deformation or yielding. The most used fibres are glass fibre and carbon fibre. Glass fibre has a higher allowable strain which can be important for spoolable pipe. Carbon fibre is stiffer and stronger but also more expensive.

For the polymer, there are two types: thermoset or thermoplastic. A main driver to select thermoplastic polymers for TCP is the ductility and high allowable strain. Thermosets such as epoxy are typically stiffer but brittle which can lead to microcracks when spooling a pipe. Processing of thermoplastics is by melting and this can be repeated multiple times. Thermosets are processed by curing which is possible only once. Spoolable composite pipe exists in both thermosets and thermoplastic, where thermoset is mostly used for onshore only. The RP-F119 is focused to *thermoplastic* composite pipe.

The composite laminate is build up in layers, or in composite terminology: plies. In a ply the fibres are uni-directional, so all in one direction. The fibres are very stiff and strong, where the polymer has much lower stiffness. This results in a *directional* strength and stiffness properties of the composite: stiff and strong in fibre direction, with lower strength perpendicular to the fibres. It also implies that the failure mechanisms are directional. For a stress in fibre tensile direction, the failure mechanism is fibre failure. For a stress perpendicular to the fibres, the fibre mechanism is first matrix yielding and ultimately matrix cracking.

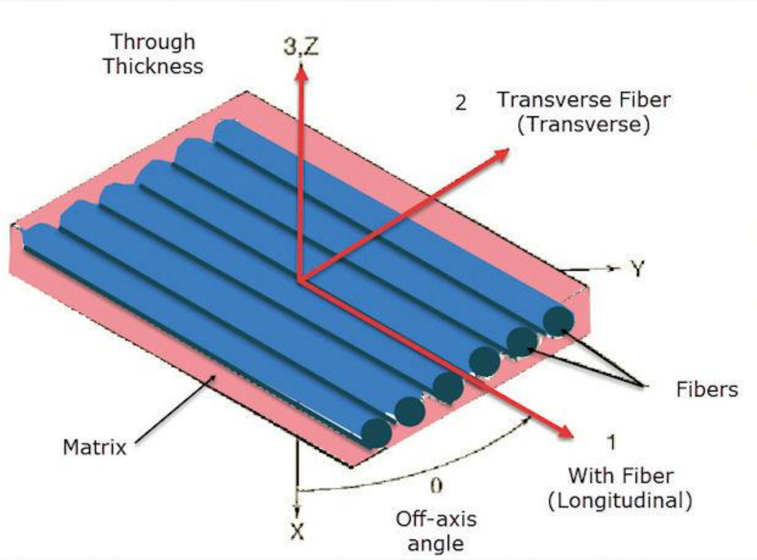



*Figure 1: Composite build-up, in fibres and polymer (matrix)*

Each layer, by nature of it being uni-directional, is applied in one layer only. In the next layer or ply, the fibres can be placed in another direction. By changing the orientations of the fibres in each ply, the strength and stiffness performance of the total laminate can be designed.

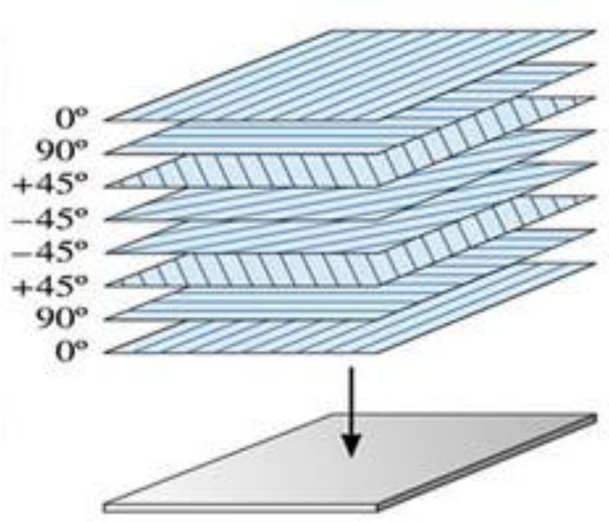



*Figure 2: A composite laminate, build up in individual plies*

In the TCP this is done by winding and melt-fusing tapes, in which the fibres are already impregnated with the polymer by the material supplier. The coordinate systems is defined as: 0° fibre angle is when the fibres are placed in axial direction of the pipe, 90° fibre angle is when the fibres are in circumferential direction of the pipe.

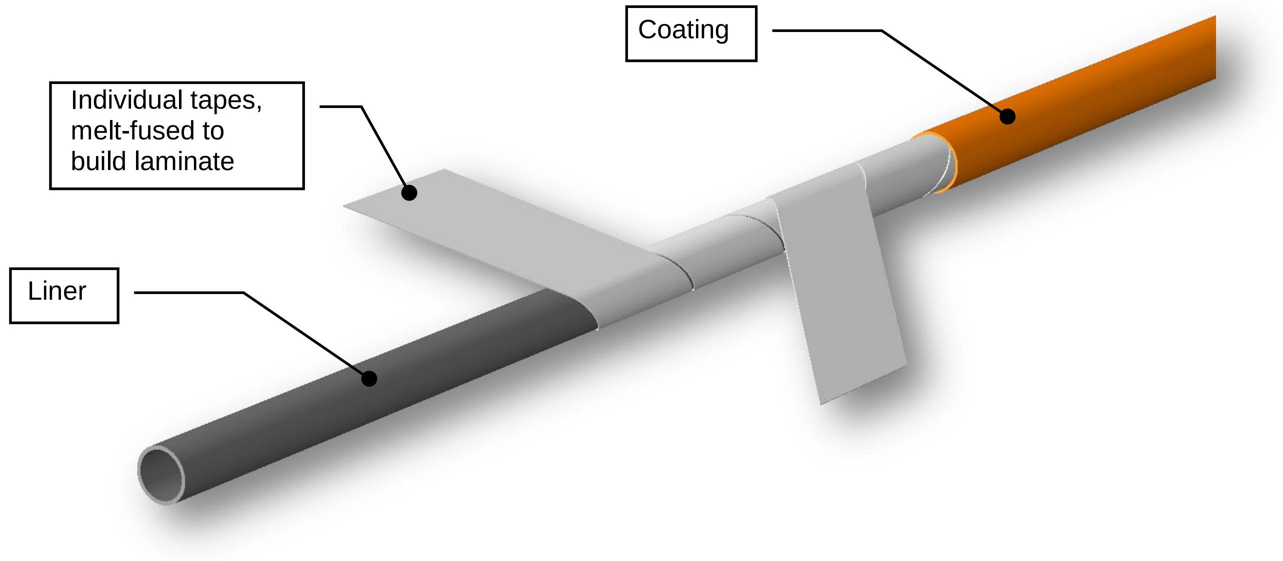



*Figure 3: Design of TCP, laminate made by winding and melt-fusing uni-directional tapes*

Airborne Oil & Gas currently uses two design concepts for the laminate:

- High-flex design: the fibres are placed in +/- 55° direction. This is a design optimised for internal pressure because the fibres are in the direction where the highest stress occurs when a pipe is loaded under internal pressure. It is also a design that has high flexibility, it is very spoolable. This design is used for products like flowlines, jumpers and spools.
- High-tension design: the fibres are placed in two directions: tensile direction and hoop direction. This design has more tensile strength capability but lower spoolability. It is used for products like risers and downlines.

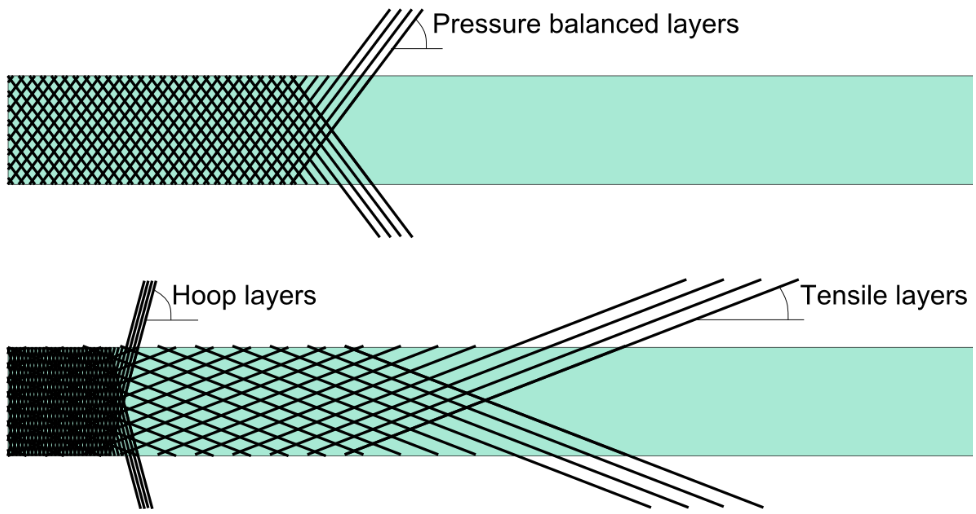



*Figure 4: High-flex and High-tension design concepts*

### 4.2 Design framework

A schematic representation of our design approach is given in Figure 5. The left-hand side presents the product, its components, functional requirements and failure modes. The right-hand side presents the application and corresponding loads and environments. By design, the strength of each individual failure mechanism must be higher than the stresses induced by the combined loads.

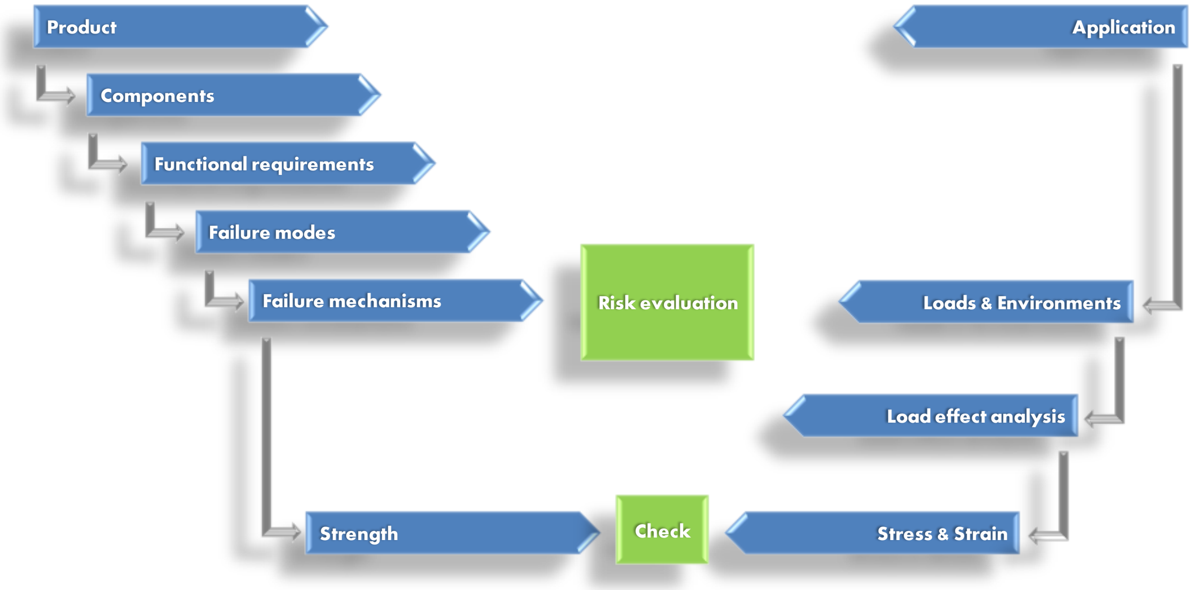



*Figure 5: Schematic representation of design approach*

Important aspects in the left-hand side of this schematic overview are:

- Breakdown of the product into several components
  - For example, the product consists of metal end fittings and the TCP itself. The TCP itself consists of a liner, composite laminate and a cover
- Determination of specific requirements per individual component
  - For example, main function of the cover is to protect the composite laminate against UV light and usage in the field
- Determination of all possible failure modes
  - Failure modes are on pipe level, for example burst or excessive deformation. The failure mechanisms are at material level, for example fibre failure or matrix (polymer) yielding. These levels are linked, whereby failure modes are underpinned by failure mechanisms: for example, matrix yielding (failure mechanism) can result in excessive deformation (failure mode) of the composite laminate
- Relation between failure modes and requirements
  - The relation between failure modes and requirements is an important aspect in determining the consequence of failure
- Determination of all possible failure mechanisms
  - Possible failure mechanisms are determined according to Section 5 of the RP-F119. One of the difference between a TCP and unbonded flexible is that failure due to friction and abrasion between unbonded layers does not occur in a TCP
- Determination of the strength of each individual failure mechanism

- The strength of each failure mechanism is measured as part of the material characterization program. The strength may depend on temperature, time (e.g. fatigue and long term continuous load) and effects of fluids (swelling, degradation)

The left-hand side of Figure 5 is product and material based and therefore independent of a specific application. The right-hand side is related to the actual application. Based on the client's specifications, a Design Basis is created, listing the loads and relevant environments during all the phases of the design life of the product. Assessment of what loads occur, and under what conditions, is a vital part of the design process; this assessment is made in the Failure Mode, Effect and Criticality Assessment (FMECA), and laid down in a design report.

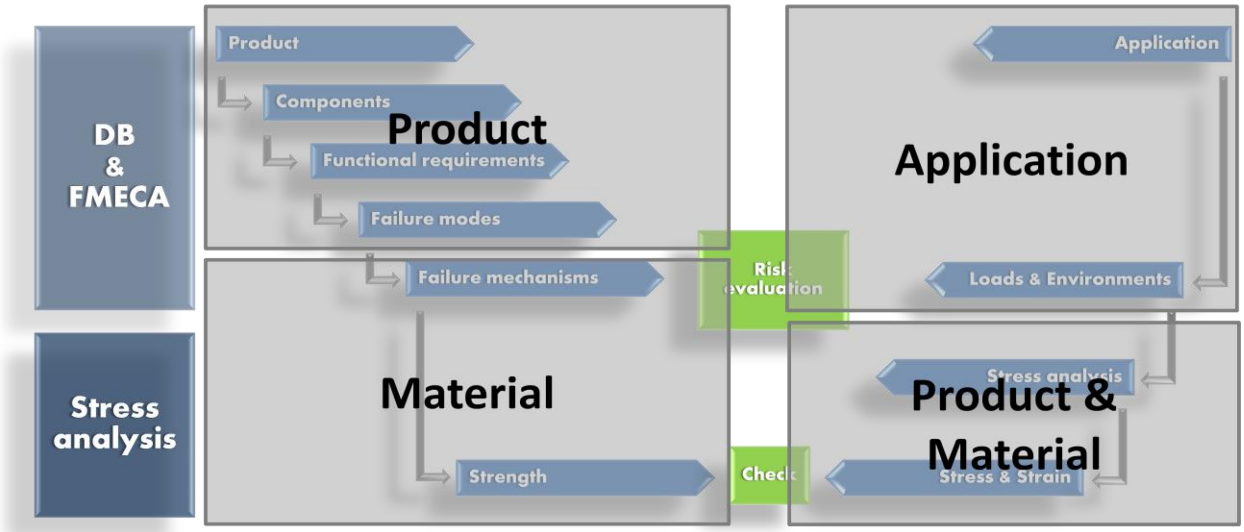



*Figure 6: FMECA and Stress Analysis*

## 4.3 Stress analysis

A representation of the final step in the design process, the stress analysis, is shown in Figure 7 below. In this step, the check is made whether the strength of the material is sufficient, including safety factors, to carry the load acting on the component. *This check is made for every individual ply, and for each individual failure mechanism*. Main elements in this overview summarised below:

- On the right, the loads acting on the component are derived from specifications and FMECA
- The loads lead to stresses and strain, depending on the stiffness of the material. At a given strain, for example induced by bending on the reel, the stress increases with increasing stiffness. Alternatively at a given stress, for example induced by internal pressure, or tension, the strain will be smaller with increasing stiffness
- For combined load cases, the stresses and strains need to be summed. Specifically for thermoplastics, the stiffness behaviour is non-linear (the stiffness reduces with strain), which has to be accounted for in accurate predictions. Further, the stiffness of the material is influenced by the environment:
  - For example, a higher temperature leads to lower stiffness of the polymer
  - For example, fluid absorption can lead to lower stiffness of the polymer

  Based on the actual test data of material coupons, a material model is created which accurately describes the material stiffness, including its non-linear aspects and influence of environment

- The strength of the material, or *resistance*, is also influenced by the same environment. The strength of the material is measured through testing of several (typically the most severe, or extreme) combinations of fluid, temperature and time. As not all combinations can be measured through testing, Airborne Oil & Gas has developed a tool that accurately predicts the strength of the material for any combination of time, temperature and fluid, by interpolation between the extremes that have been tested

Following the design approach of the RP-F119, each TCP is designed such that none of the fundamental failure mechanisms at material level will occur during its design life, taking into account the safety factors. As long as those failure mechanisms do not occur, the corresponding failure modes at TCP level will not occur and every component of the TCP will be able to fulfil its function during the design life. Airborne Oil & Gas designs its TCP's such, that no failure modes occur during the design life; for instance, matrix cracking or delamination is not allowed to occur during its design life.

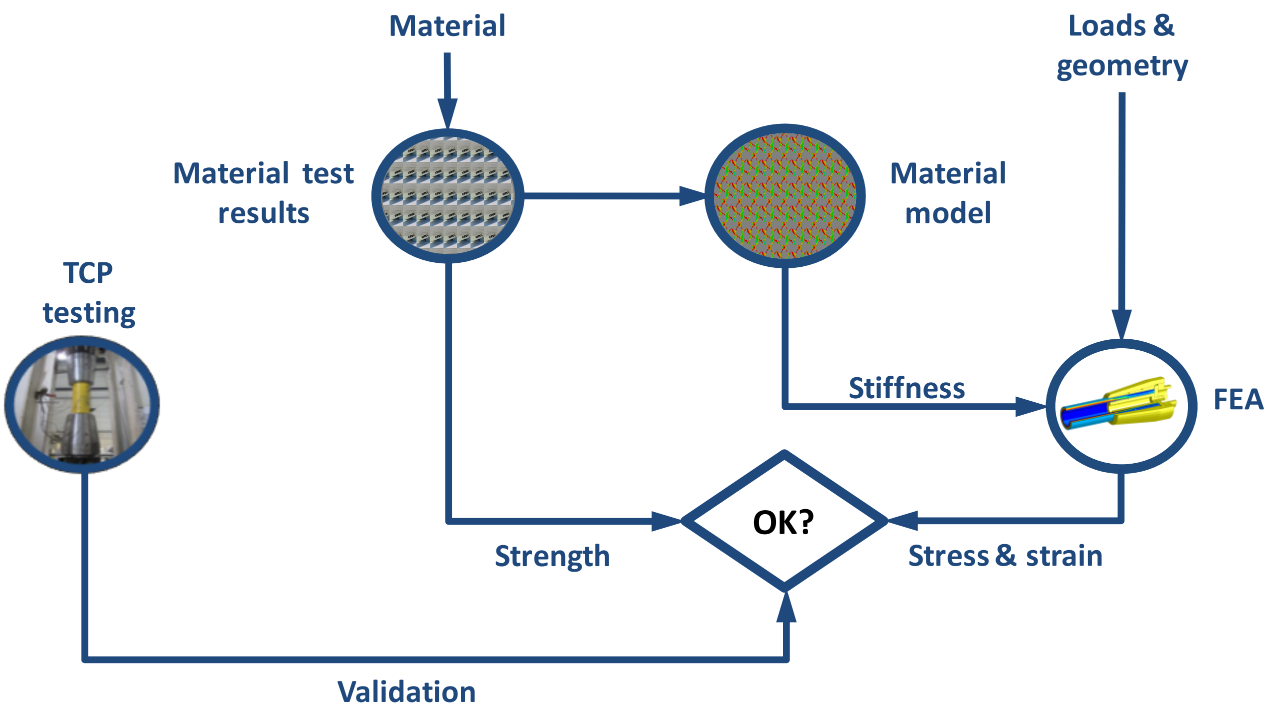



*Figure 7: Stress analysis*

### 4.4 Safety factors

On performing the check between strength and stress, there should be sufficient safety factor. The safety factor approach followed by the RP-F119 uses partial and model safety factors that are to be satisfied. The magnitude of the safety factors depend on the following:

- Accuracy of the magnitude of the load. For example, external pressure as result of water depth is very accurate and not easy to exceed for a given length of pipe. Or, bending of a pipe over a barrel of a given reel results in an accurate strain.

- Fatigue and stress rupture, being specific long term loads, are more difficult to accumulate over time, hence attracts a larger safety factor.
- Accuracy of the failure criterion used in strength predictions.
- Nature of failure, e.g. a brittle failure attracts a higher safety factor than a ductile failure.
- System build up. Depending on how a system is built up from components, the likelihood of failure can be higher for the system than for the components.

Safety factors can also be derived from the standard OS C501. For bending on the reel for instance, Airborne Oil & Gas derives the safety factors from OS C501.

Finally, depending on the criticality of the application, the client sets the safety class at High, Medium or Low. The safety class reflects the consequence of failure. This further influences the total safety factor.

# 5 Qualification Testing

## 5.1 Introduction

As shown in Figure 7 and Figure 8, the RP-F119 approach includes testing both on material as well as product level.

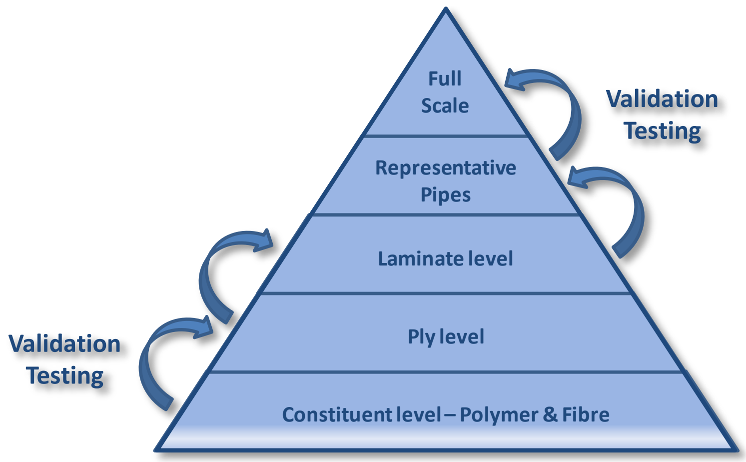



*Figure 8: Test pyramid as per DNVGL-RP-F119*

## 5.2 Material testing

As described in the previous section, it is important to accurately establish the strength of each individual failure mechanism, as part of the design process. This is done through extensive material qualification testing. Many tests are performed at the lower (material) scales and less tests at the higher scales. Test data from lower scale can be used at higher scales only if design models used to predict the performance at higher levels are validated; for instance, one must prove through testing that the performance at laminate level can be accurately predicted using data from ply level, and so forth. The validation requirements are quite strict as will be discussed in the next section.

The material testing program determines the strength of each individual failure mechanism, like fibre tensile failure, fibre compressive failure, delamination, matrix cracking, matrix yielding and polymer fracture. Not only the short term strength is measured, but also long term strength, such as stress rupture/creep strength  and cyclic fatigue strength. The effect of temperature is included by testing both at minimum and maximum design temperature. In addition, all tests are performed in dry condition and exposed to worst-case fluid from the application. For instance, stress rupture tests are performed on coupons that are submerged in the actual fluid while being loaded up to 10,000 hours.

If a TCP will continuously be exposed to a certain fluid, the material strengths measured on coupons exposed to that fluid are used in the design. As such, Airborne Oil & Gas assumes that the TCP is fully saturated during it's entire life. In the future, the design methodology can evolve taking into account diffusion gradients through the thickness.

A complete material testing program, conducted to satisfy the RP-F119 requirements for one material, includes thousands of tests and takes about 1.5 years to complete. Once finished, the data can be used for all products made from that material. Airborne Oil & Gas is independent from the material and always selects the most cost effective and fit for purpose material for each application; to date, we have qualified our first material and are continuously testing other materials as well.

In the graphs below some examples of material testing are shown (note that the dots with arrows are still running tests):

- Figure 9 shows the measured fatigue performance of stress level due to tension, plotted against the number of cycles to failure. This is done for the composite E-glass fibre in a PolyEthylene matrix (EGF-PE).At lower tension load, the material can endure more tensile fatigue cycles before failure. The effect of fluid (saturated samples)is included in the graph
- Figure 10 plots the stress rupture, *or fibre creep*, against time. A fibre cannot hold a certain constant tension indefinitely; at lower tension load, the fibre can support the load for a longer length of time.

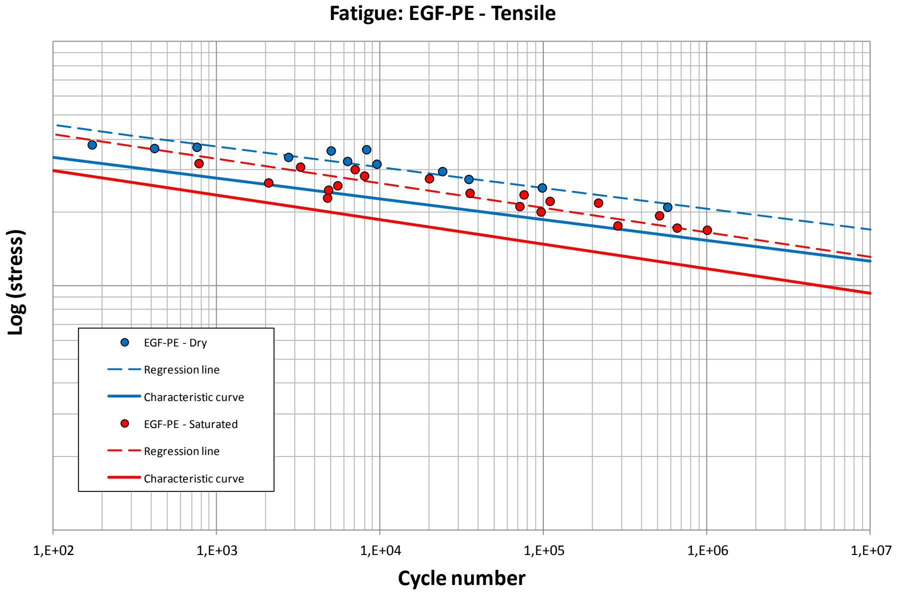



*Figure 9: Fatigue testing on material, Dry and saturated.*

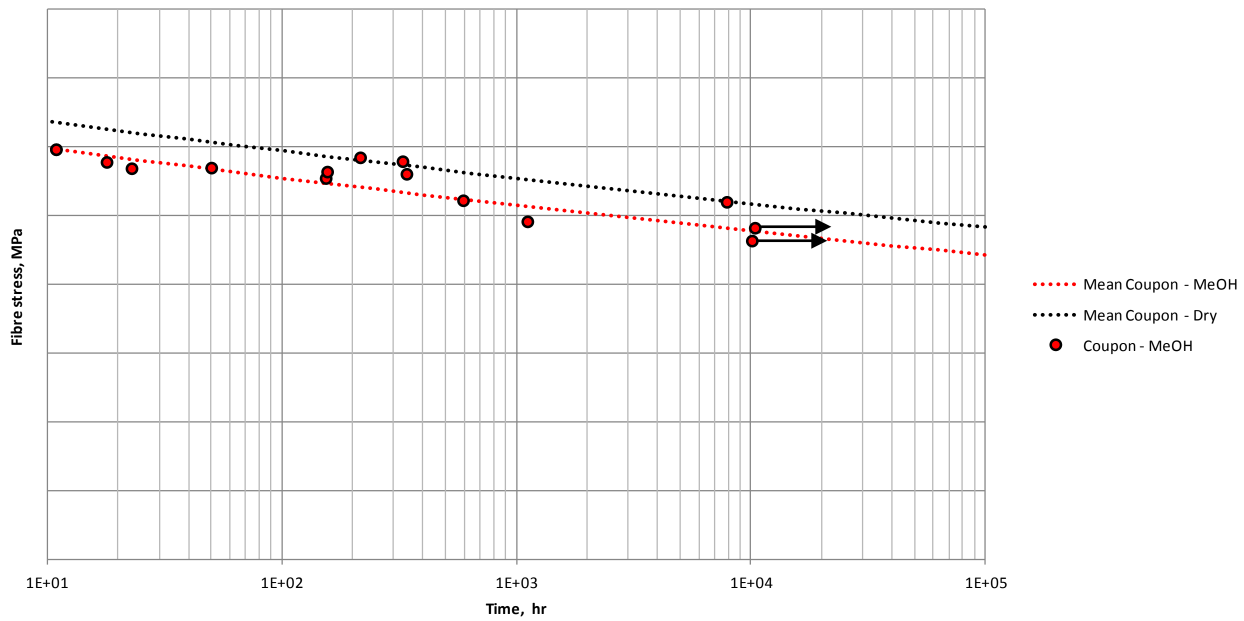



*Figure 10: Stress rupture testing, in Methanol*

## 5.3 Product testing

During the design phase, stresses and strains in the TCP are determined for each individual composite layer. The strength of an individual layer has been determined by the material characterization program. As a result, the strength of the full scale TCP can be predicted for any given load combination. An important aspect of the product qualification testing is to validate that the measured full-scale performance is in line with the predicted (calculated) performance. Once this equivalence is proven, all other design calculations for other load cases are validated.

The test acceptance criterion for a full-scale validation test is as follows:

- The failure mechanism shall be as predicted. If e.g. fibre tensile failure is predicted as critical failure mechanism, the test is only accepted if the TCP indeed fails due to fibre tensile failure
- The failure load (level) shall be as predicted. The measured value shall be within ± 1 STD of the calculated value. The STD is the standard deviation of the material strength as measured during the material testing program. In order to eliminate other statistical variations, the as built dimensions of the TCP shall be used in the calculations.

This implies that if a burst pressure of e.g. 2000 bar is predicted whereas the TCP actually failed at 2900 bar (being outside the predicted range), the test is not accepted. Main reason for not accepting an “outperforming” pipe is that the designer clearly does not understand the full-scale behaviour sufficiently accurate.

In the graphs below some examples are shown of the relation between material data and full scale pipe testing:

- Figure 11 shows the test data of actual pipe burst tests against the finite element model, based on material coupon data. The statistical variation on material level is translated to the same variation for burst pressures on pipe level
- Figure 12 shows the stress rupture data of actual pipe, showing the correlation between material testing and pipe testing. The pipe is tested by internal pressure, leading to stress in the wall of the pipe

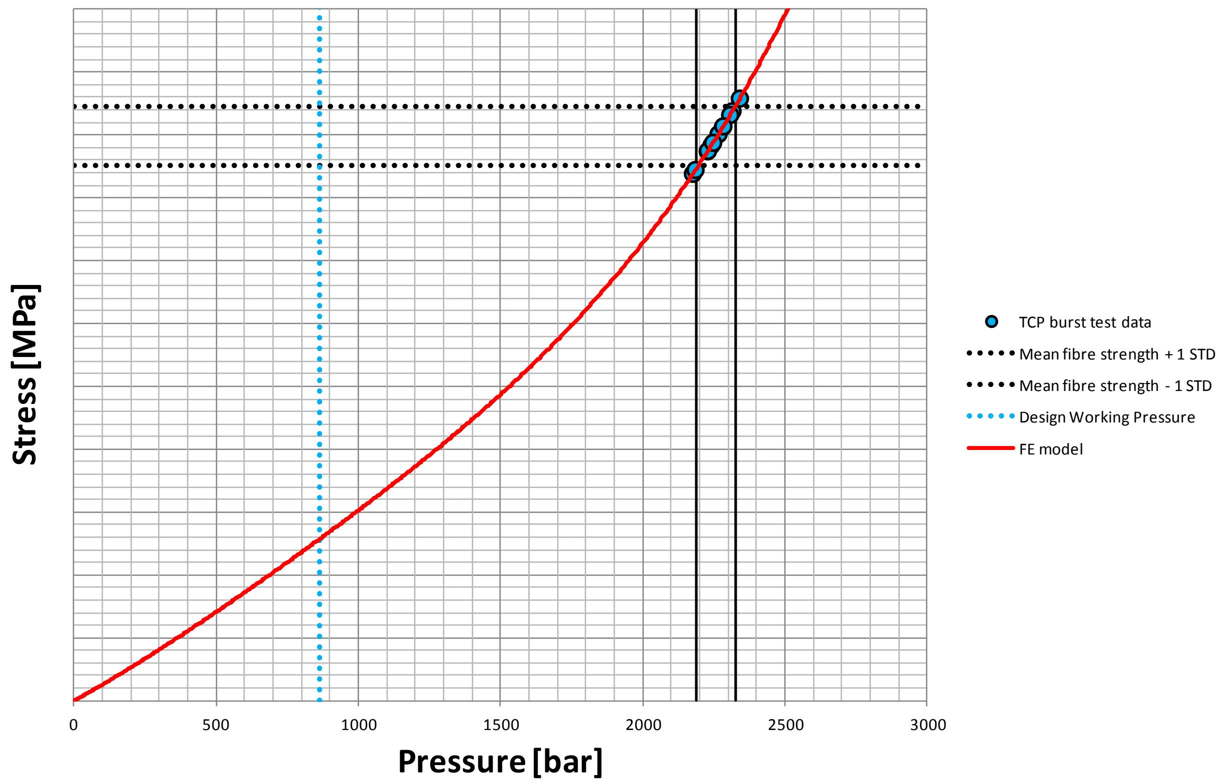



*Figure 11: Correlation between prediction (red line) and pipe testing for a 10ksi pipe (690 bar)*

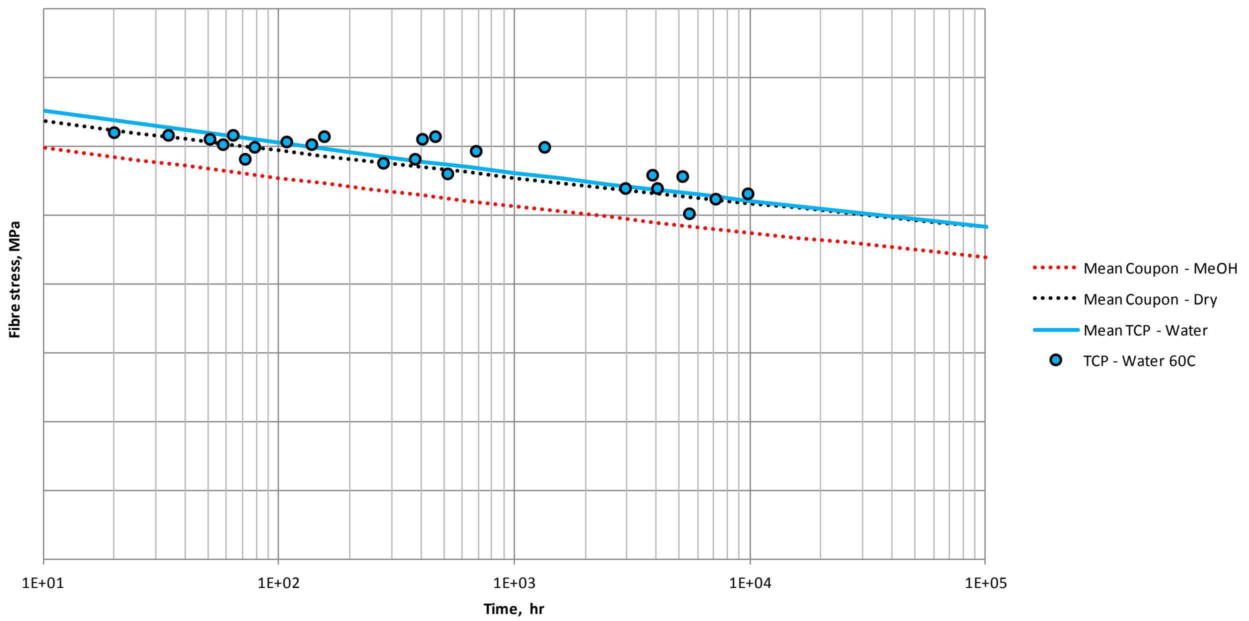



*Figure 12: Stress rupture testing on pipe level*

A typical full-scale product qualification test program consists of the following tests:

- Burst test. Both at minimum and maximum design temperature
- Burst under bending
- Cyclic fatigue survival test (max. 100,000 cycles)
  - Bending cycling with and without internal pressure
  - Axial tension cycling with and without internal pressure
  - Internal pressure cycling
- Stress rupture survival test (max 1,000 hr)
  - Bending stress rupture with and without internal pressure
  - Axial tension stress rupture with and without internal pressure
  - Internal pressure stress rupture
- External pressure test up to failure
- Determination of bending, axial and torsional stiffness if required

Both cyclic fatigue tests and stress rupture tests have a maximum on the number of cycles / duration during the test. Instead of testing even more cycles the magnitude of the load during the test is increased. This is allowed as long as the critical failure mechanism is the same in the test compared to the actual design load case that the test should represent. Herewith, the cost and duration of the qualification program is reduced.

The applied load level is chosen such that the test consumes the complete design life of the TCP. The TCP should survive this test, for it should be capable of carrying the load during its complete life; this test therefore is called “survival test”. Upon completion of the test, with the pipe still intact, a residual burst test is performed. The acceptance value for the residual burst is equal to that of a virgin pipe. Thus, the survival tests prove that the performance of the TCP does not reduce after having consumed its whole fatigue design life.

For some design aspects it will be impossible to calculate the TCP behaviour sufficiently accurate. Examples are impact load and Rapid Gas Decompression (RGD). In such cases, separate qualification tests have to be performed on product pipe samples. Main difference with the other qualification tests is that these tests are not *validation* tests since they do not validate design calculations.

## 5.4 Type Approval

Airborne Oil and Gas has carried out a qualification program to certify its design methodology, production and materials according the RP-F119. Those aspects are essential to qualify a specific TCP product and can be seen as the *generic* part of the qualification, see Figure 13. Early 2016 Airborne Oil & Gas has received the DNVGL certificates for the generic parts.

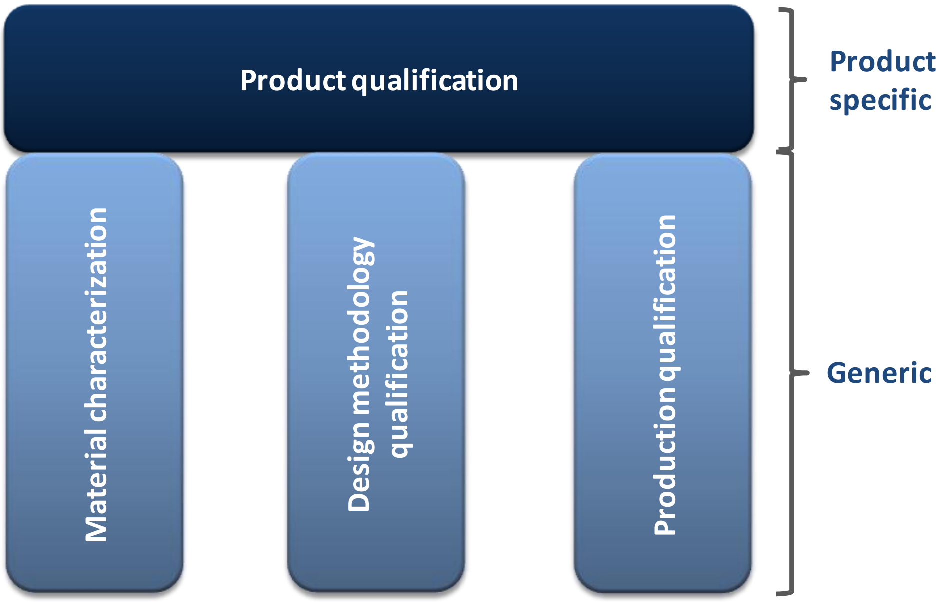



*Figure 13: Qualification approach: generic and product specific parts*

# 6 Conclusions

The RP-F119 builds on having a fundamental understanding of the design, materials and production of the TCP. The RP addresses all potential failure mechanisms at material level and their consequences at TCP level. This bottom-up approach ensures that all TCP failure modes are covered. Thanks to the solid, monolithic wall structure consisting of many individual layers, the TCP behaviour is easily predictable and scatter in testing is surprisingly small.

Airborne Oil & Gas, the first and leading manufacturer of TCP, has qualified its design method, production process and first material in compliance to this RP-F119. Through this, Airborne Oil & Gas have demonstrated its capability in qualifying TCP, and proven the effectiveness of this Recommended Practice.

In order to share our experience and drive the adoption of TCP in the market place, Airborne Oil & Gas has build a comprehensive information package on the design and qualification of TCP. We make this available to the industry in a variety of ways, including training sessions, technical events, and lunch & learns. These packages cover not only the theoretical way of designing and qualifying, but include specific example cases of how products have been qualified in reality.

These events allow you to learn more about TCP, what it can do for you in your operations and how to design and qualify TCP. Interested? Then please contact us for more information.

Airborne Oil & Gas

# A Information Request – Technical Events – Training

Airborne Oil & Gas provides training sessions to the Oil & Gas Industry on the design and qualification of Thermoplastic Composite Pipe (TCP). The level of training can be tailored to the client's specific needs and existing level of understanding. The sessions can be at any level, such as:

- Lunch & learns, whereby a general introduction is given at a fairly low detailed level
- Technical Events, generally hosted by Airborne in IJmuiden, The Netherlands. Technical Events typically consist of a (tailored) training program
- Training course composite pipe design for subsea flowline and riser applications

Both the Technical Events en The training will focus on technical aspects of design and qualification of TCP in accordance to DNVGL-RP-F119 and hence be non-commercial.

**Application**

As the course will show, TCP pipe systems will be designed and qualified with certain applications in mind. For this training course, the focus is in the SURF area, mainly subsea Spools, Jumpers Flowlines and Risers.

**Curriculum**

The following aspects will be covered in this course:

- Basics in composite design
- General concept of the Thermoplastic Composite Pipe
- Design methodology following DNVGL-RP-F119
    - Basis of Design & FMECA
    - Load effect analysis
    - Design report
    - Test plan
- Design Tools:
    - FE model TCP & End-Fitting
    - Material model
    - Strength predictions
        - Static, creep, fatigue, ageing
        - Fluids, time
    - Effects of defects & thermal stresses
- Failure modes & failure mechanisms
- Offshore installation
- On-Bottom Stability
- Integrity management

At the completion of the course, some generic business cases will be built by the course attendants.

**Time, duration & venue**

The following options are available for this composite pipe design course:

1. At Airborne Oil & Gas premises. Dates available upon request.
2. At other venues available globally.

**Public**

The course is intended for the following groups:

- Pipeline Engineers
- Pipeline Technical Authorities
- Pipeline Subject Matter Experts
- Subsea Engineers
- Engineering Managers
- Research and Development Managers
- Polymer Experts
- Installation Engineers
- Material / Corrosion Engineers

**More information:**

For more information, please send an email to info@airborneoilandgas.com.