A NEW RECOMMENDED PRACTICE FOR THERMOPLASTIC COMPOSITE PIPES

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ABSTRACT

Thermoplastic composite pipes (TCP) are a new class of pipes for the offshore industry. They are used to transport oil, gas and water. A new recommended practice, RP, has been developed giving design criteria and test requirements for TCP. This paper gives an overview of the approaches taken in the RP.

The RP´s default qualification approach is based on predicting full-scale performance from data obtained from measurements on the material level. Some full-scale and medium-scale testing is required to confirm that the predictions are valid. This approach is known as the "test pyramid" in many industries. Advantages and challenges of the test pyramid approach for TCP are being discussed.

In the new RP, the process of characterization of TCP materials for service in various environments is described. The RP puts special emphasis on long-term properties. The results of the material tests are used in design requirements for the components of the TCP that are linked to failure criteria on the material/component level.

A limited number of full-scale prototype tests is required to confirm that the design calculations based on material data obtained from small-scale specimens (or subcomponents) predict the actual performance. The philosophy and challenges related to this approach are discussed.

1 INTRODUCTION

Thermoplastic Composite Pipes (TCP) are a new class of flexible pipes. The pipes are typically manufactured by winding fibre reinforced thermoplastic tapes around an inner liner. The liner and the tapes are fused together forming a bonded structure. An outer cover is also often applied. A simple schematic of a TCP is shown in Figure 1. It shows a cut of the TCP together with an example of a simplified end fitting. The TCP can be many hundred meters long; in principle a TCP has no length limit. The pipes can be used in many applications such as risers, flowlines and jumpers. The TCP share lightweight and high specific strength with bonded thermoset composite risers. By putting no fibres into the axial direction and utilizing the typically high strains to failure of thermoplastics the TCP are more flexible than traditional composite pipes made from thermoset resins and they can be reeled. TCP are more flexible than traditional solid composite or steel pipes, but they are a bit less flexible than flexible steel pipes made of interlocking segments.

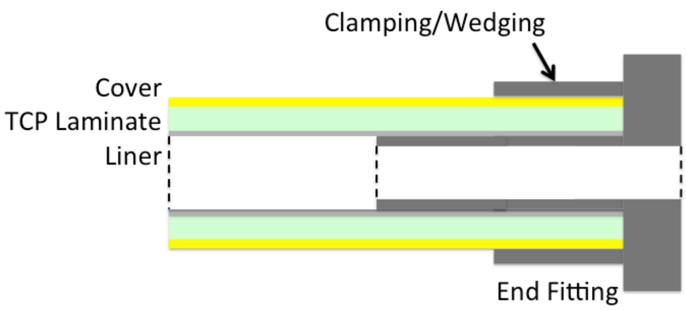

Figure 1: Schematic of a TCP with a simplified end fitting, from DNVGL-RP-F119 [1]

A new Recommended Practice RP has been developed for designing and qualifying bonded Thermoplastic Composite Pipes (TCP). It is the result of a Joint Industry Project with 18 participants. It is published as an official DNV GL recommended practice, denoted DNVGL-RP-F119 “Thermoplastic Composite Pipes” [1]. The main applications covered in the RP are offshore transporting water, oil and gas. The new RP covers the gap between API 17 J [2] for unbonded flexible pipes and DNV-RP-F202 [3] for thermoset composite risers. The RP is based on the philosophy of the DNV GL offshore standard DNV-OS-C501 “Composite Components” [4]. This paper gives an overview of the scope and content of the new RP and how it relates to RPs and standards for related products. Furthermore, it describes important technical details that are specific to TCP.

2 SCOPE AND CONTENT OF THE RECOMMENDED PRACTICE FOR TCP

This RP describes requirements for TCP for offshore applications. It provides the design philosophy, specifications of loads and structural analysis. It addresses testing and performance characteristics of TCP´s materials and pipes. A brief description of the content is given in Table 1. This paper concentrates on the materials related aspects. Information about TCP applications can be found in [5-8].

Part	Section
Initial Part	General Design Philosophy
Development Part	Design basis Materials, including test requirements Failure mechanisms and design criteria Analysis methodology Design criteria for pipe body and end fittings Performance based qualification – full scale testing only
Testing	Prototype test requirements
Safety factors	Safety factors
Final Part	Operational phase: inspection, maintenance, repair Production QA test requirements Marking and Packaging Documentation

Table 1: Brief description of the contents of the Recommended Practice for TCP.

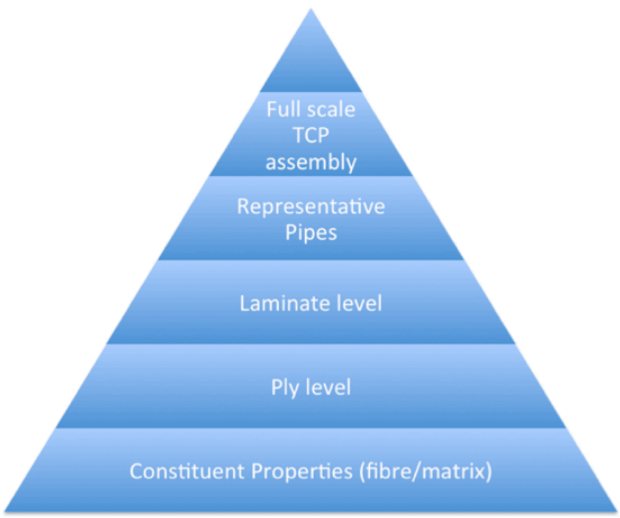

Figure 2: Design pyramid, as given in DNVGL-RP-F119 [1]

3 MATERIALS PROPERTIES

The RP´s default qualification approach is based on predicting full-scale performance from data obtained from measurements on the material level. Ply properties and laminate through-thickness properties are seen as the material level in this RP. Theses properties are also typically the main input in finite element based design calculations. Some full-scale and medium-scale testing is required to confirm that the predictions are valid. This approach is known as the "test pyramid" in many industries. The RP´s test pyramid is shown in Figure 2. The advantage of using the pyramid approach is that testing can be done relatively quickly and cost effectively on small test specimens.

The design strengths used in the RP are characteristic values x_c determined as the sample mean $\bar{x}$ minus k_m sample standard deviations of a test series.

$$x_c = \bar{x} - k_m \cdot \hat{\sigma}$$

The coefficient k_m depends on the number of measurements, the safety class and the failure type [1, 4, 9]. It decreases with an increasing number of tests, because the confidence in the results improves by testing many specimens. This approach is similar to the A and B design values used in the aerospace industry [10]. Testing many specimens is preferred, because k_m decreases. Testing many small specimens is much easier done than testing larger components. The manufacturer/designer can choose how many tests he/she wants to perform giving a balance between the test effort and penalty put on calculating the characteristic value. However, it should be noted that a large number of tests does not necessarily result in a higher characteristic design value (although it very often does), because the sample mean value may change as the number of tests increases due to the natural scatter of the test results.

Testing unidirectional plies or laminates for obtaining design input can be experimentally challenging. The RP allows testing cross-plied or other laminate configurations if the unidirectional ply properties can be back calculated from the laminate's test results.

Testing small flat specimens for obtaining ply properties is known to many test laboratories. The question remains whether the specially made flat specimens properly represent the materials used in the wound TCP. Following the test pyramid approach the RP requires some tests on simplified or actual pipes to check whether the ply properties from flat specimens are representative. For static properties the required tests on pipes are (presented slightly simplified here):

- Axial compression tests
- Internal pressure tests
- Hoop strength tests
- Crushing ring tests

Failures should be predicted from the ply properties within an accuracy of ±1 standard deviation of the materials data. This should ensure that the combination of the modelling approach and the ply data are sufficiently accurate for the product. If the correlation is achieved the materials data can be used for many projects giving a significant reduction in testing effort. It may happen that the performance of the pipe cannot be predicted from the material/ply properties. The reason could be too large differences in the production process or a model that does not accurately predict nonlinear effects. In this case the RP allows using pipe data for the design. However, using pipe data typically reduces the range of applicability of the data to unknown load cases. It also increases the complexity of testing.

Through-thickness properties need to be tested if they are critical for the structural integrity. They may not be critical for the pipe body, but they are typically critical at the transition between pipe body and end fitting. If the liner or cover is part of the loading path, their properties need to be established too. Through thickness properties need to be tested on wound pipes, because the effects of fusing the layers together cannot be predicted from investigating ply properties.

Long-term data, such as fatigue and stress rupture data, need to be measured as well. Similar to static properties, long-term data can be measured on the ply level. Confirmation testing is required on the pipe level. The required tests are:

- Internal pressure tests
- Axial compression tests
- Axial tensile tests

The loading conditions shall be chosen based on the mean ply data that cyclic testing lasts 10^5 cycles and stress rupture testing lasts 1000 hours. The cycles or time to failure shall be within one standard deviation of the predictions. If test data and predictions do not agree, all long-term data may be obtained from pipes. But it is clearly much more convenient to obtain data on the ply level.

The RP also gives the option to perform all testing on large- or full-scale TCP. The advantage of this approach is that the actual product is tested. But the test results are only valid for the loading conditions and environments tested. If the application of the TCP is represented by the tested conditions the approach is viable. If the application has additional conditions it is difficult if not impossible to address these extra conditions based on the full scale testing.

4 TEST ENVIRONMENTS

All materials testing described in Sections 3 and 4 of this paper shall be done in the relevant environments that the TCP experiences. Typically water is on the outside and hydrocarbons in the inside. Temperatures range from cold water to hot fluids. High temperatures due to sunlight exposure or storing under arctic conditions may also be relevant. Testing under all these conditions can quickly result in large test programs. The RP gives guidance on how the test programs can be reduced by considering the most critical fluids and extreme temperatures. Special care has to be taken for thermoplastic systems that may be used below and above the glass transition temperature. All materials have to be saturated with the respective fluids before testing starts. Further, long term tests need to be carried out in the respective environments; otherwise the test specimens would dry out during testing and would not give the proper properties. Experience has shown that especially carrying out long-term testing in hydrocarbons has been a challenge for the testing laboratories, but it can be done. Material properties need to be obtained also for dry conditions, because this reflects the conditions of the TCP at the beginning of the lifetime and full-scale prototype testing can only be done under dry conditions (see also Section 8).

The extensive test programs have created a desire to reduce the testing effort. A possibility could be to test degradation of fibres and matrix separately. Ply properties would then be predicted from the properties of the degraded constituents. The degradation of the constituents could possibly be predicted by chemical reaction kinetics, creating basically a multiscale approach. Some steps in this direction are currently on the way [11] and the RP opens for this approach in principle. Only limited and relatively simple testing of ply properties would be needed to confirm the predictions from the multiscale approach. This is a promising approach, but it will take some time until this can be used with confidence.

5 DESIGN CRITERIA

The TCP used in offshore applications needs to fulfil a number of design and functional requirements. The requirements are listed in the leftmost column in Figure 3. The design requirements are given on a high level and they need to be considered for all components of the TCP. The design criteria need to be linked to specific failure mechanisms, as shown in the rightmost column of Figure 3. The user focuses on the design criteria and wants to be ensured that they are all fulfilled. The technical design engineer focuses on demonstrating that the failure mechanisms influencing the design criteria will not happen during the lifetime of the TCP.

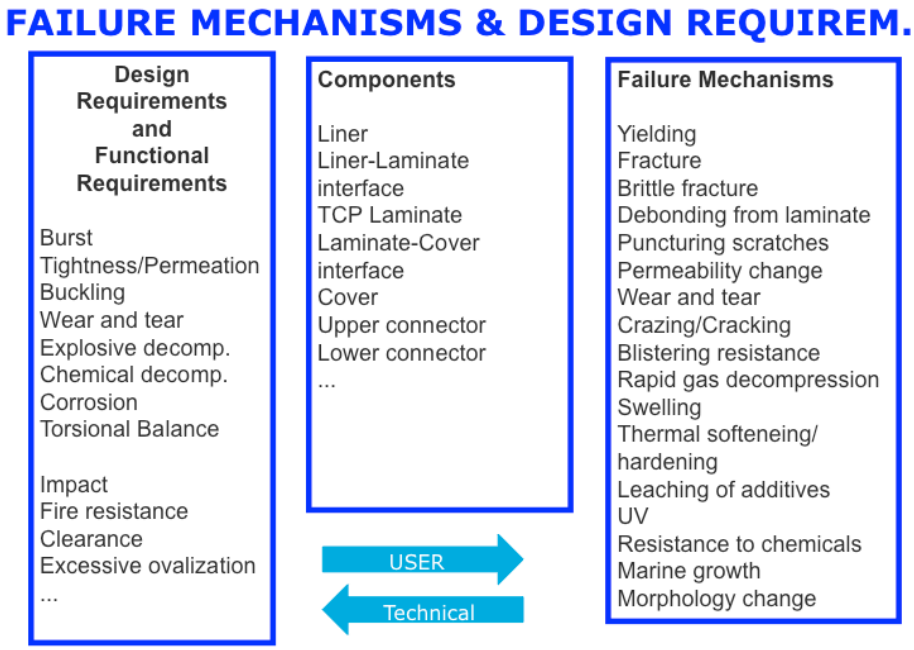

Figure 3: Design criteria and Failure mechanisms described in DNVGL-RP-F119.
They shall be checked for all components shown.

For example, a key design criterion is that the TCP should be fluid tight. If the TCP has no liner, extensive matrix cracking and fibre failure would cause leakage. If the TCP has a liner matrix cracking can be acceptable, but fibre failure would also result in leakage and total failure. The RP has procedures for checking the various possibilities of finding the critical failure mechanisms for the particular design and application.

The failure criteria are applied to local load effects, i.e. they are applied on the ply level. Strength values are characteristic strengths or strains to failure obtained by material testing. Failures shall be checked for all loading conditions and all material conditions (degraded, undegraded). The failure criteria also include safety and model factors applied to load effects and strengths. Most criteria are close to the well-known failure criteria used for composites, sometimes slightly simplified.

In order to allow reeling with a small radius, TCP have typically no fibers running directly in the axial direction. A typical layup could be of the form $[\pm 85_n, \pm 45_m]_k$ where fibre directions are given relative to the long axis of the pipe. When applying axial loads or bending the pipes could experience large plastic deformation making laminate theory calculations invalid. To limit the axial deformations a laminate failure criterion has been introduced in the RP checking the strain in the axial direction for these types of laminates. Note that testing ±45 laminates is used to determine in plane shear properties of the matrix, the failure is matrix dominated [12]. When testing a ±45 wound pipe in the axial direction the fibres run continuously from one end of the pipe to the other, giving possible fibre failure together with large deformations.

All critical failure mechanisms need to be checked also for long-term performance. This is done by using SN curves, Goodman diagrams and Miner sum calculations.

6 SAFETY FACTORS

Safety factors are given as partial safety factors using the partial safety factor format. They were calibrated to specified target safety levels for typical TCPs and applications. Different load factors for pressure, functional and environmental loads allow for an optimal design. The resistance factors are given for different safety classes. The different safety classes reflect different degrees of severity of the consequences of failure. The resistance factors also change with the coefficient of variation of the strength of the materials. Model and system factors are also given. This paper does not focus on safety factors, but it should be mentioned here that the variety of factors is needed to reflect different applications and different material and manufacturing methods. Using only one set of factors could be unsafe or excessively conservative.

7 END FITTINGS

End fittings are typically made of metal. The design of the metal part is outside the scope of the RP and other standards should be used. But the composite metal interface is an important aspect of the design and of this RP. A schematic of a simplified end fitting is shown in Figure 1. It can be seen that axial loads need to be transferred through the composite metal interface and by through thickness shear. Actual end fittings use more detailed solutions and may involve also clamping and friction, but the principle remains the same.

All design criteria and failure mechanisms identified for the pipe body need also to be checked for the end-fitting region. In addition a Failure Mode Evaluation Analysis (FMEA) is required to identify possible other failure mechanisms for a specific end fitting solution. As a minimum the following aspects shall be evaluated:

- Fluid tightness between metal parts and the TCP components.
- Ballooning (the pipe expanding outwards at the pipe-to-end fitting transition).
- Effect of welding of metallic parts on the composite.
- Axial, torsional and bending capacity.
- Galvanic protection.
- Effect of friction.

An end fitting has many stress concentrations and interfaces, which are difficult to model. For this reason much of the full-scale prototype testing is done to check whether the design models can simulate the performance of the end fittings.

8 FULL-SCALE PROTOTYPE TESTING

The main purpose of full-scale prototype testing is to verify the main loading conditions and to verify the design analysis. The following tests are specified and listed here in a simplified way:

- Burst test
- Burst test under bending
- Axial force test
- Cyclic fatigue survival tests (axial, bending and pressure), followed by a burst test
- Stress rupture survival tests (axial, bending and pressure), followed by a burst test

In some cases tests can be waived if the loading conditions are not relevant for the application.

Tests are specified to be done at various temperatures. Pressure tests are done with water and the TCP is always dry (except for the exposure to water during testing). It should be noted that testing full-scale samples in saturated conditions is not practical, because reaching saturation of thick laminates may take many years. Saturating the laminates inside the end fittings may take even longer. This shows the importance of comparing the test results with simulations. If the test results can be properly predicted by the simulation methods it is shown that the tools describe the complicated conditions in an end fitting properly. The analysis tools can then be used with much better confidence to predict performance of the TCP and the end fitting when environmental degradation has happened based on the material test data under those conditions. It is also impossible to test all loading conditions of a TCP. Also here simulations need to be used to evaluate the load conditions that cannot be tested.

In order to qualify the analysis methods predictions of the test results shall be done within the accuracy of one standard deviation. The standard deviation is estimated from the relevant material data. For example, the burst pressure of a pressure test should not be lower and not be higher than the predicted mean pressure ± one standard deviation. This is a rather tough requirement on the analysis capabilities, but it should ensure that the analysis could also predict other loading conditions reasonably well.

The fatigue and stress rupture tests are survival tests. The test conditions are chosen by the same principle as for the static tests, fatigue lifetime should be predicted within plus/minus one standard deviation for a given loading condition. However, here only the minimum performance is checked, because the samples are not tested to failure.

In addition to the tests mentioned above a few performance-based tests need to be done:

- Torsional balance test
- Gauge test
- Impact or resistance to trawling test, followed by a burst test.

It is important that all full-scale prototype test samples are made by the same production procedures and equipment as used for later fabrication. The RP requires also some additional testing for production control.

9 CONCLUSIONS

The recently published recommended practice provides a basis for qualification of the new TCP. For the first time, structural thermoplastic materials are being qualified for offshore applications using an appropriate RP. The RP is performance-based, allowing different product developments and innovations. The novel aspects of the RP compared to the existing practices for thermoset composites are discussed in the paper.

ACKNOWLEDGEMENTS

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