THERMOPLASTIC COMPOSITE PIPE: ANALYSIS AND TESTING OF A NOVEL PIPE SYSTEM FOR OIL & GAS

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SUMMARY
A novel spoolable pipe system for the oil & gas industry has been developed: thermoplastic composite pipe, which is a single-polymer, fully bonded fibre reinforced pipe concept produced with a continuous winding process. A non-linear analysis tool has been developed and correlated with tests.

Keywords: composite, thermoplastic, pipe, analysis, testing

PIPE CONCEPT
The thermoplastic composite pipe concept (Figure 1) consists of an inner liner, thermoplastic composite reinforcement layers and an outer coating [1],[2]. All layers are of the same thermoplastic polymer and are welded together during the production process to form a solid, fully bonded laminate. This secures the strongest interface possible between the layers, prevents any rapid gas decompression problems and creates excellent collapse resistance.

Figure 1 Thermoplastic composite pipe concept

Using thermoplastic composites has advantages in spoolability, impact resistance (toughness), fatigue and chemical resistance. Furthermore, it is possible to weld pipe sections together, integrate end connectors or use standard metal connectors. Applications for this pipe system are in on- and offshore flow lines, downhole coiled
tubing, intervention lines and offshore risers, especially for deepwaters and high pressures.

**ANALYSIS TOOL**

The behaviour of a thermoplastic matrix system is much more non-linear than of traditional thermoset matrix systems like epoxy. The stress-strain curve is non-linear; thermoplastics have a plastic material behaviour and a visco-elastic behaviour (creep), which can be more prominent depending on the material. Therefore, a dedicated pipe analysis tool has been developed, which incorporates this non-linear behaviour. It covers both stress-strain non-linearity as well as time non-linearity. Since the geometry is simple and always a pipe, the tool has been set-up as a fully analytical tool allowing for faster design optimisation than with FEA methods. Multiple failure criteria are incorporated, such as Tsai-Hill, maximum strain and stress, pipe buckling and fibre buckling. The fibre buckling is a phenomenon, which applies particularly with thermoplastics, when using relatively low stiffness polymers like PP or HDPE.

**TESTING AND CORRELATION**

A rigorous testing campaign was set-up and is currently in execution. Test cases contain tension, axial compression, internal and external pressure, torsion, bending and bending with internal pressure. Static load, fatigue loading and long term testing have been carried out. Testing is performed to qualify specific products and to monitor product quality variation during production. Besides that, tests are performed for correlation of the analysis to obtain a generic design tool. A wide range of designs and materials is produced and tested, ranging from glass-HDPE to carbon-PEEK. In this paper, glass-PP pipes will be discussed. The correlation of the analytical tool for tension, axial compression and internal and external pressure will be discussed, since these are the primary load conditions applied to the tubes. The collapse due to external pressure is given most attention.

**Tension**

In the figure below the result of a tensile test on a ±55° glass-PP specimen is shown. Three predicted failure points are indicated: Tsai-Hill, and matrix yield for the minimum and maximum principal strains (11 and 22 respectively).
The non-linearity of the analytical prediction can clearly be observed and is caused by the stress-strain relation of the material, as shown in Figure 3. However, the analytical prediction is not accurate over the whole strain envelope. The interpretation of this deviation above approximately 1% axial strain is that it is caused by shearing of the fibres and geometrical non-linearity, which is not yet taken into account in the analysis model.

Tsai-Hill is a good indicator when the deviation from the prediction starts. It should be noted that the laminate is not damaged yet, as would be the case with thermosets. This has been validated with residual strength testing after fatigue above the Tsai-Hill point, and no reduction in ultimate strength is observed. It appears that the matrix is ductile enough to allow the shearing of the fibres.

The Tsai-Hill criterion gives a safe design with large reserve capacity with respect to ultimate strength and with this, strains remain limited. When tension is a critical loadcase, unidirectional fibres can be applied in axial direction and fibre failure will become the governing failure mode.
Compression

The result of an axial compression test on a ±55° glass-PP sample is shown in Figure 4 below. Also indicated in this plot are the Tsai-Hill, matrix yield and fibre buckling failure modes. The analytical prediction is essentially the same as for tension, since the analytical tool uses the same material data.

![Figure 4 Comparison between analytical prediction and test results for compression](image)

The figure shows a large deviation from the test result above approximately 1.5% strain. Most of this deviation is caused by the fact that the analytical tool is not yet suited for compressive material data. In addition, the geometrical changes during loading (including fibre shearing) are not taken into account. None of the failure modes approximates the compressive strength of the sample. Tsai-Hill provides a conservative approximation of where the deviation between the test and the prediction starts and where strains are limited.

In the future, the analytical model shall incorporate both the updated geometry (including fibre shearing) and the compressive properties of the constituent materials. These modifications will improve the predictions of the tube behaviour in both tension and compression.

Internal pressure

In Figure 5 below, the analytical predictions for the various failure criteria are presented for the burst strength of a ±55° tube sample. The result from an actual internal pressure test is also indicated. The fibre angle is optimised for internal pressure and consequently fibre failure is the intended failure mode. Fibre failure is indeed observed from the damaged specimen, as shown in Figure 6. Ply shear and transverse strength are higher than the fibre criteria and will not occur. Tsai-Hill and matrix yield are predicted at a
lower level, however, these do not predict the actual failure, which is fibre failure. Again, this is attributed to the large ductility of the matrix.

The analytical prediction for fibre failure is conservative. The mismatch between the prediction and the test result is caused by scatter in the test results, variations in production and material properties, non-linearity of the geometry and the fact that the geometry is not updated in the analysis. These effects are not yet included in the analytical model. The model incorporates empirical correlation factors to match the predictions to the test results. This correlation for the fibre failure criterion has been performed and is shown in Figure 7 below.
Figure 7 Correlation analytical prediction and test result for internal pressure

**External pressure**

A comparison between the analytical prediction of the collapse strength of a specimen and the actual test results is presented in Figure 8. Again, the tests are performed on ±55° glass-PP specimens. The external pressure is applied hydrostatically.

Figure 8 Comparison between analytical prediction and test results for external pressure

The figure shows that all failure criteria (without safety factor) overestimate the collapse resistance of the tube samples. Examination of the actual failure mode of the collapsed tube learned that local buckling is the governing failure mode for external pressure. An example of a collapsed specimen is shown in Figure 9.
From theory, it is shown that local buckling precedes fibre buckling as critical failure mode for this type of tube. A safety factor of 1.5 is applied to the local buckling failure criterion, ensuring a conservative prediction of the collapse strength of the tube samples. This result has been validated for a multitude of tube samples.

**Material variations**

As mentioned before, the thermoplastic composite pipe consists of an inner liner, thermoplastic composite reinforcement layers and an outer coating. The reinforcement layers are constructed from glass-PP prepreg tapes. Inspection of the thermoplastic tapes show differences in fibre volume fraction ($V_f$) and thickness. Part of the variations in material properties is caused by the fact that the tapes are obtained from larger (wider) tape rolls, where the whole roll has an average $V_f$ and thickness. The distribution over the width however varies.

Fibre volume fraction and thickness of the tapes are measured during inspection. The analytical predictions of for example the burst and collapse strength of the tubes are based on these measured rather than on the nominal values to obtain a valid correlation of the tool.

It was previously stated that fibre failure is the governing failure mechanism for the burst strength of the tube samples. Differences in fibre volume fraction or tape thickness will therefore have a direct effect on the burst strength, since these parameters determine the amount of fibres in the product and the stress to which these fibres are loaded. The combined effect of the fibre volume fraction and tape thickness can be evaluated by the fibre content of the samples.

In Figure 10, an overview is presented of several tube products with varying fibre volume fractions and tape thicknesses. It can be observed that large variations exist in the burst strength of these products. Also plotted in the same figure is the fibre content of these products. The fibre content shows a direct relation to the burst pressure of the various samples. This supports the hypothesis that fibre failure is the governing failure mode in predicting the burst resistance of the tubes. It can also be seen from the figure that one product (S41) shows a slightly higher burst pressure than would be expected.
based on its fibre content. Apparently, this tube performs slightly better on internal pressure than its predecessors. For this product, an improvement of production process has been implemented, and this is directly affecting the quality of the product.

![Graph showing relation between fibre content and burst strength of tube samples](image)

**Figure 10 Relation between fibre content and burst strength of tube samples**

**Geometry deviations**

Similar to the incoming inspection on the materials, an outgoing inspection is also performed to ensure product quality. An important geometrical parameter for this is the ovality of the tube. Ovality as defined by API [3] is:

\[
\text{ovality} = \frac{D_{\text{max}} - D_{\text{min}}}{D_{\text{max}} + D_{\text{min}}}
\]

where \(D_{\text{max}}\) and \(D_{\text{min}}\) represent the maximum and minimum diameter of the tube respectively. The maximum allowed ovality is 0.75%. Ovality can be caused by e.g. production, coiling or otherwise handling of the tube.

Since collapse of the tube due to external pressure was shown to be the result of local buckling, ovality will have a large impact. This is shown in Figure 11 where the ovality is plotted against the collapse strength of ±55° glass-PP specimens.
A clear trend of reduced collapse strength for increased ovality is visible in this graph. Of course, test data include some scatter around the trend. This scatter can be explained by the varying fibre volume fraction and tape thickness of the samples. Smaller tape thickness results in a smaller outer diameter, which will influence the buckling behaviour of the sample. A better indication of the effect of ovality on collapse resistance can be obtained by plotting the ovality against the ratio of the test data and the analytical prediction. In this ratio, variations in fibre volume fraction and tape thickness are incorporated, giving a more normalised result. The relation between ovality and this ratio is presented in Figure 12 below.

The figure shows the separate data for two products. A linear trend can clearly be observed. For both products, a perfectly round sample (zero ovality) would result in the
same ratio of test over prediction. Recall that the safety factor applied to the local buckling failure criterion is 1.5 and compare this to the ratio at zero ovality. This shows that the initial failure criterion (local buckling without safety factor) provides a slightly lower (and thus conservative) collapse strength for a perfectly round tube. The analytical tool however can simply be correlated to match this prediction with the test results.

Combination of this prediction for perfectly round tubes with the slope of the ovality curve for similar products results in the collapse strength at arbitrary ovality. Note that this slope still varies for the two products. The difference is caused by variations in the production process such as laminate quality and precision of winding. Apparently, the collapse strength of product S40 is less affected by ovality than for product S41.

CONCLUSION

A spoolable composite pipe system for the oil & gas industry has been developed. This single-polymer, fully bonded pipe system consists of an inner liner, thermoplastic composite reinforcement layers and an outer coating. A fully analytical tool has been developed to predict the non-linear behaviour of the tubes. This analytical tool incorporates the various failure modes of composites to predict the behaviour of the various load conditions. Furthermore, the tool is correlated with a multitude of test results.

This paper has shown that correlation of the analysis with test results provides an effective prediction tool. Taking into account material and geometric variations, such as fibre volume fraction, tape thickness and ovality of the tube, results in a generic analytical tool. For fully predicting axial tension and compression, the analytical tool must incorporate both compressive material properties as well as geometrical effects such as fibre shearing. For now, the tool allows for fast design optimisations for multiple load conditions.

References


3. API-5L ‘Specification for Line Pipe’.