A MICROMECHANICS APPROACH TOWARDS DELAMINATION OF THERMOPLASTIC COMPOSITE PIPE FOR OFFSHORE APPLICATIONS

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ABSTRACT

Airborne Oil & Gas is the world's first and leading manufacturer of fully-bonded thermoplastic composite pipes (TCP). This lightweight, flexible composite pipe is enabling for deeper water exploration, production and intervention, and puts an end to corrosion. Serious efforts have been put into qualification testing according to the qualification pyramid of a very large amount of coupons testing, a moderate amount of mid-size testing (small-scale pipe) and a set of full-scale pipe sample testing mainly for validation purposes. This approach has only been possible with state-of-the-art analysis techniques that can well predict the performance of the pipe in the application. One of the more difficult failure mechanisms to predict is the delamination of the pipe, which may result from excessive crushing of the pipe during installation (*e.g.*, tensioner, buoyancy elements, over the chute) or impact during operations for example.

Delamination is a matrix dominated failure mechanism – however, brittle in nature, which is usually caused by out-of-plane shear stress in the composite lamina. A multi-scale material model of the composite based on the material properties of the constituents (*e.g.*, fibers and matrix) is developed. Given a multi-scale material model, delamination is addressed directly at the micro-level (*i.e.*, the constituents level), where the matrix strength is utilized as the governing strength parameter. Moreover, manufacturing imperfections (*e.g.*, voids) can occur which adversely affect the delamination strength, and are accounted for in the model.

In the present study, virtual testing of the TCP subjected to a lateral crushing load-case is carried out, where the failure is governed by the delamination of composite layers as observed experimentally. The predicted TCP response is compared with the experimental observations, and the onset-of-failure along with the location of delamination are verified. A good correlation has been found between the finite-element predictions and experimental observations.

1 INTRODUCTION

Airborne Oil & Gas is the world's first and leading manufacturer of fully-bonded thermoplastic composite pipes (TCP). Our unique continuous manufacturing process produces a fully-bonded, solid wall pipe with glass or carbon fibre reinforcements completely embedded within the thermoplastic material, see Figure 1. The pipe's polymeric inner liner, composite laminate and external coating are all melt-fused, which provide strong and robust spoolable pipes of continuous length, see Figure 1. The TCP – a lightweight and spoolable composite pipe – is enabling for deeper water exploration, production and intervention, and puts an end to corrosion.

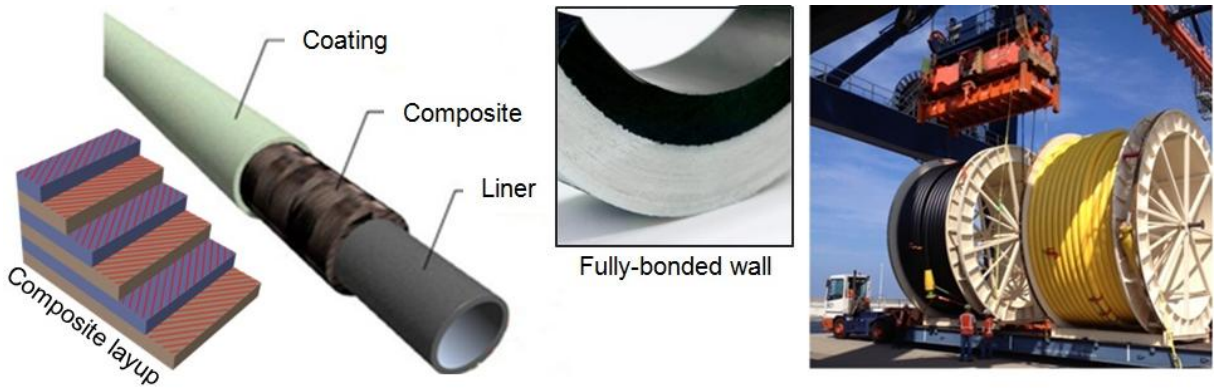

Figure 1: An illustration of the thermoplastic composite pipe consisting of a polymeric liner and a coating, which is reinforced with the composite laminate, see the left panel. The reinforcement consists of many composite layers of a designed layup, where the red lines represent the respective fiber orientation for a layer. The TCP have the full-bonded sold wall (see the middle panel) and have excellent spoolability, see the right panel where 6" inner diameter TCPs are shown.

Understanding and predictability of the system is a key ingredient in qualification of any new technology. In accordance with DNVGL RP-F119, a pyramid (the building-block) approach for design and qualification is used. Extensive material testing and modelling forms the basis to accurately predict the TCP's full scale performance. Product qualification consist of a limited number of carefully selected full scale validation tests. However, it can only be achieved with predictive engineering coupled with multi-scale modelling in case of composite structures, see the left panel of Figure 2.

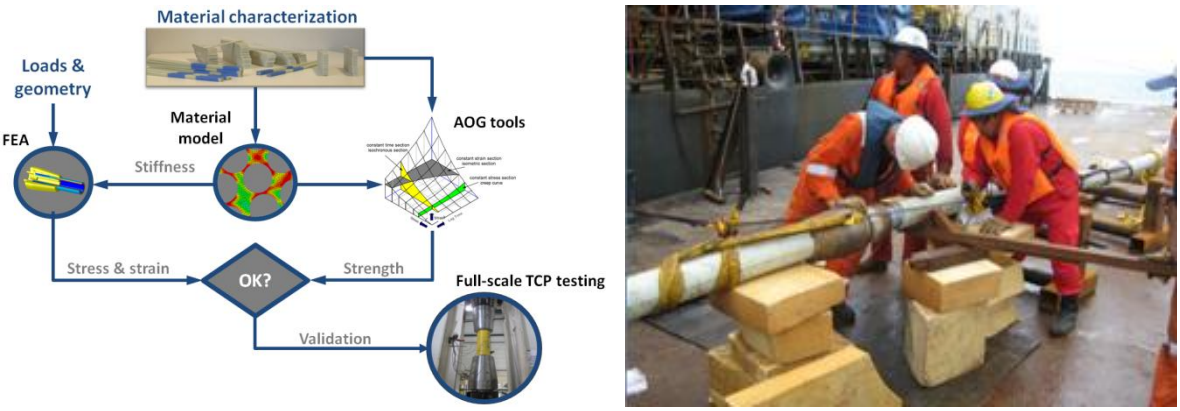

Figure 2: From numerical analysis, coupon testing to small-scale testing and validation (see the left panel) to the actual application in the field (see the right panel). The TCP design methodology accounts for all possible failure modes and mechanisms, where the material strength and stress/strain predictions (via finite-element results) are compared to determine the safety margin for a given design and application specific loading, see the left panel.

The predictive engineering is an integral part of the TCP design methodology, for which various analysis tools have been developed. The analysis tools are obtained after rigorous work including testing (coupon as well as full-scale), finite-element modelling and validation, see the left panel of Figure 2. For the TCP, serious efforts have been put into qualification testing according to the qualification pyramid of a very large amount of coupons testing, a moderate amount of mid-size testing (small-scale pipe) and a set of full-scale pipe sample testing mainly for validation purposes. This approach has only been possible with state-of-the-art analysis techniques that can accurately predict the performance of the pipe in the application, see Figure 2. One of the more challenging failure mechanisms to predict is the delamination of the pipe, *i.e.*, separation of plies or bonded laminate. Delamination may result from excessive crushing of the pipe during installation (*e.g.*, tensioner, buoyancy elements, over the chute) or impact during operations for example, *e.g.*, see the right panel of Figure 2.

Various failure theories have been suggested in the literature [1-2] to predict the failure of anisotropic heterogeneous composite materials, which are either energy-based (*e.g.*, Tsai-Hill, Azzi-Tsai-Hill, Tsai-Wu, etc.) or failure-mechanisms-based (*e.g.*, Hashin, Hashin-Rotem, Puck, etc.). Failure-mechanisms-based failure criterion relies on the fact that in the most fiber reinforced composites, there is a clear distinction between fiber and interfiber (matrix, interface) failure mechanisms, which allows the treatment of failures in a more physically-significant fashion. The interfiber failure mechanisms strongly depend on the matrix properties and three-dimensional stress-state of the composite, which govern the fracture plane and ductile or brittle nature of the failure, and has been given special attention in the literature [1-2].

Delamination is a matrix dominated failure mechanism – however, brittle in nature, which is usually caused by out-of-plane shear stress in the composite lamina. The interlaminar strength can be obtained via interlaminar shear strength (ILSS) coupon testing. However, imperfections (*e.g.*, voids) do occur during manufacturing of composites, which will reduce the delamination strength of the composite causing the delamination to occur at a relatively lower stress-state. As damage initiation will happen at the micro-scale, the stress-state of the constituents can be checked against their strength parameters, *e.g.*, matrix stress for the delamination failure. To facilitate, a multi-scale material model has been developed for the composite material, which allows access to the stress-state of the constituents (*e.g.*, matrix and fibers).

In the present study, we will show the predictive engineering solutions for delamination failure of the TCP. Moreover, a micromechanics approach is being followed where the delamination is addressed directly at the micro-level (*i.e.*, the constituents level) and the matrix strength is utilized as the governing strength parameter. Furthermore, the influence of the manufacturing imperfections (*e.g.*, voids) is also accounted for. For validation, virtual testing of the TCP subjected to a lateral crushing load-case is carried out, where the failure is governed by the delamination of composite layers as observed experimentally. Finally, a comparative summary is presented, where the predicted TCP response is compared with the experimental observations.

2 TCP DESIGN AND PREDICTIVE ENGINEERING

The predictive engineering is an integral part of Airborne Oil & Gas's design methodology, for which various analysis tools have been developed. The analysis tools are obtained after rigorous work including testing (coupon as well as full-scale), finite-element modelling and validation, see the left panel of Figure 2. The design methodology accounts for all possible failure modes and mechanisms, where the material strength and stress/strain predictions (via finite-element results) are compared to determine the safety margin for a given design and application specific loading, see the left panel of Figure 2. Although the geometry and fibre orientations of the TCP are rather easy to model in a finite-element framework, the design of a TCP is more complicated. The challenge is mainly related to the complexity of modelling and predicting the thermoplastic composite material behaviour. Accurate

modelling of the material behaviour is of primarily importance for successful design, virtual testing and qualification of the TCP.

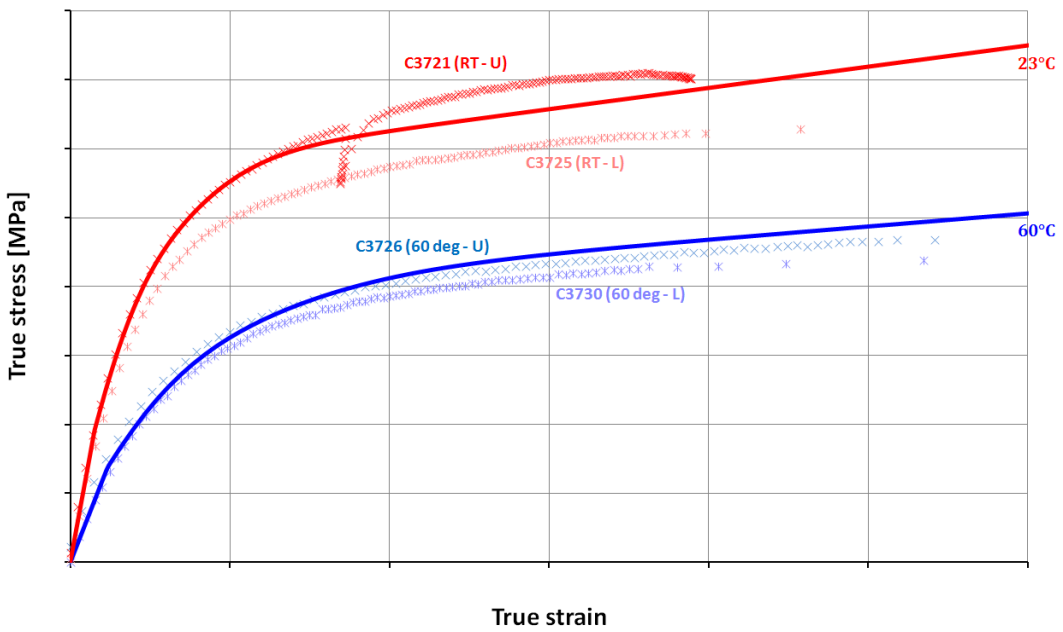

Figure 3: The thermo-mechanical composite material models (represented by the solid lines) are developed through mean-field homogenization via Digimat and using the experimental coupon data (represented by the symbols).

Constituents of the composite material (*e.g.*, fibers, matrix) govern the overall material response, thus a building-block approach is often deployed where the composite material response is calibrated at the constituents or coupon level, and then utilized to design and analyze large-scale products. In the present study, the composite material models have been developed through multi-scale modelling using Digimat, which are later used in a finite-element framework to characterize the TCP response. We have utilized the coupon test data to develop the thermo-mechanical material models (via Digimat), see Figure 3, and relevant strength parameters for the structural design and qualification, see the left panel of Figure 2. Thus developed material models are then used in Abaqus (as a user material) to design the TCP for various applications and also for the qualification.

3 MICROMECHANICS APPROACH TOWARDS DELAMINATION

One of the more challenging failure mechanisms to predict is the delamination of the pipe, *i.e.*, separation of plies or bonded laminate. Delamination may result from excessive crushing of the pipe during installation or impact during operations for example. The interfiber failure mechanisms (*e.g.*, delamination) strongly depend on the matrix properties and three-dimensional stress-state of the composite, which govern the fracture plane and ductile or brittle nature of the failure. Delamination is a matrix dominated failure mechanism – however, brittle in nature, which is usually caused by out-of-plane shear stress in the composite lamina. As damage initiation will happen at the micro-scale, the stress-state of the constituents can be checked against their strength parameters, *e.g.*, matrix stress for the delamination failure. To facilitate, a multi-scale material model has been developed for the composite material (see Section 2 and Figure 3), which allows access to the stress/strain-state of the constituents (*e.g.*, the matrix and fibers).

To determine the delamination strength interlaminar shear strength (ILSS) coupon testing is carried out. The coupon data is utilized in combination with virtual testing (via finite-element analysis) of the ILSS tests to establish the composite delamination strength. Note that it is important here to account for the material nonlinearity, which affects the shear stress distribution in the ILSS coupons. Note that the formula's given in the corresponding ASTM standard to directly calculate the strength based on the measured load during testing, is based on the assumption of linear elastic material behaviour. Next, given a multi-scale material model the delamination failure is addressed directly at the micro-level (*i.e.*, at the constituents level), and the governing matrix strength, $\boldsymbol{\sigma}_{\text{Matrix}}$, is established subsequently via correlation with the composite delamination strength.

Moreover, imperfections (*e.g.*, voids) do occur during manufacturing of the thermoplastic composite, which will reduce the delamination strength of the composite causing the delamination to occur at a relatively lower stress-state. In the present approach, the influence of the voids is considered via a micromechanics based strength reduction factor. Furthermore, the ILSS coupon data together with the void information[‡] at the TCP level is considered to obtain the upper and lower strength limits, which will be utilized in the failure predictions.

4 CASE STUDIES: VALIDATION AT THE TCP LEVEL

For the TCP qualification, the TCP samples are subjected to the lateral crushing load-case, see Figure 4 where the experimental test setup is shown. The typical test output is the load-displacement curve indicating the onset of delamination and subsequent failure. The image analysis also provides the location of delamination relative to the load application points, see the left panel of Figure 5.

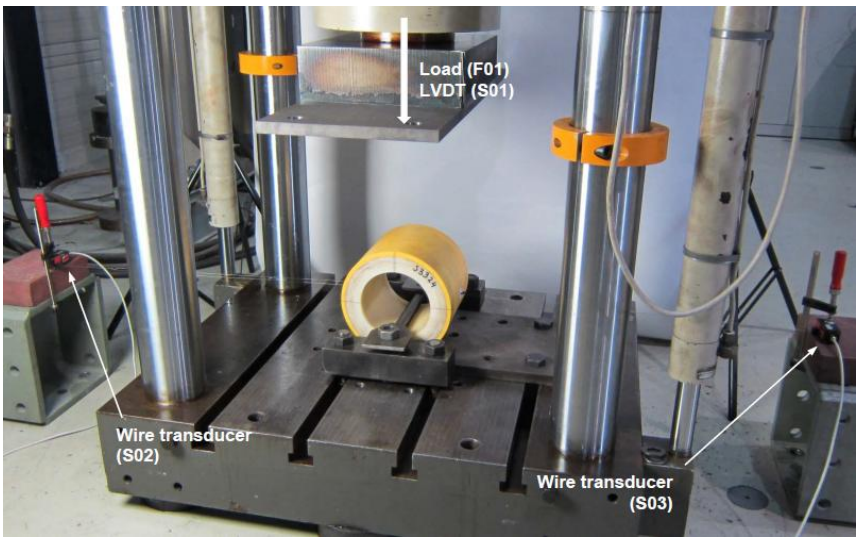

Figure 4: The test setup for the lateral crushing load-case, where the TCP sample would be subjected to a crushing load via two parallel plates. The typical output is the load-displacement curve indicating the onset of delamination and subsequent failure.

In the finite-element framework virtual testing of a TCP sample subjected to the lateral crushing load-case is carried out, where the failure is governed by the delamination of composite layers as observed experimentally, see Figure 5. The location of delamination relative to the load application points in the TCP samples is nicely correlated, see Figure 5.

[‡] Note that the void content and their distribution depend on the designed layup of the reinforcement and the manufacturing process settings.

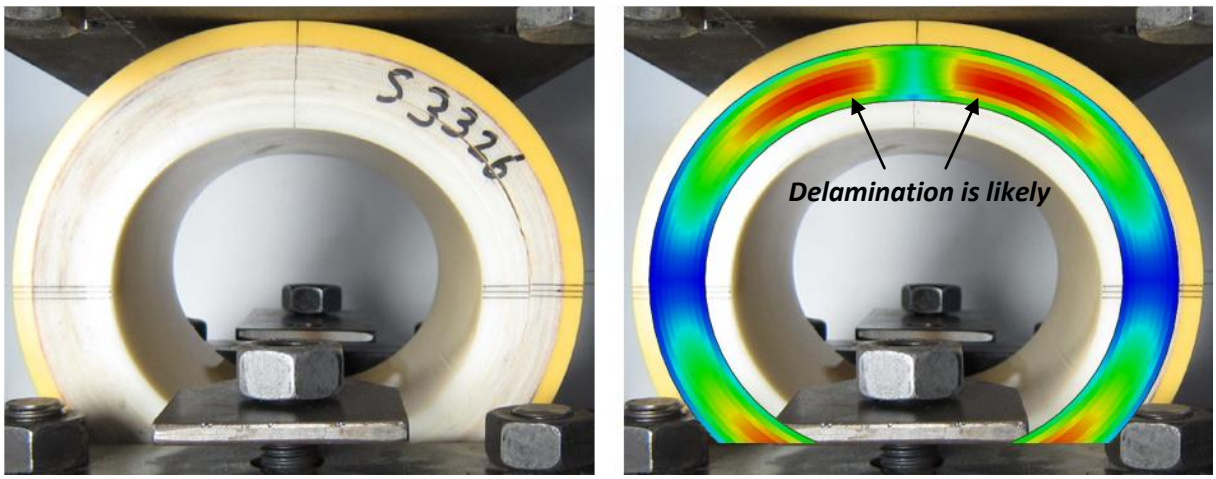

Figure 5: A 6" TCP subjected to the lateral crushing load-case. *Left*: The failed test sample indicating the delamination location. *Right*: The finite-element predictions and the stress-state within the reinforcement, where the contour colours represent the stress value with red and blue being the high and low (or zero) values, respectively.

The predicted load-displacement response is compared with the experimental observations (see Figure 6), where the onset-of-failure is also indicated. The upper and lower limits for the failure are determined, see Figure 6, based on the governing matrix strength (*obtained using the coupon data and including the effect of manufacturing imperfections*, see Section 3). The comparative summary of the results with the experimentally measured failure levels are given in Table 1. Interestingly, the transverse shear stress in the composite – that is commonly accepted as the "key driver" for the delamination failure – peaks at the same location(s) where the micro-mechanical matrix stress is maximum, see Figure 7. Clearly, there is a good correlation between the finite-element predictions and experimental observations. Based on these results (*i.e.*, predictions on the thin walled, thick-walled and different diameter pipes) the analysis suite of failure mechanisms has been extended to include delamination in the prediction of Airborne TCP for the highly demanding offshore applications.

Measured failure level			**Finite-element predictions**	
Mean	Stdev	Samples	Onset-of-Delamination	
100	3	15	91	← *Lower limit*
			98	← *Mean strength*
			107	← *Upper limit*

Table 1: Comparative summary of the experimental observations and finite-element predictions for the lateral crushing load-case, where the data is normalized *w.r.t.* the experimental mean. Note that the results correspond to 15 samples of a 2" TCP that were tested at room temperature. The onset-of-failure is predicted based on the matrix based delamination strength while accounting for the manufacturing imperfections (*e.g.*, voids).

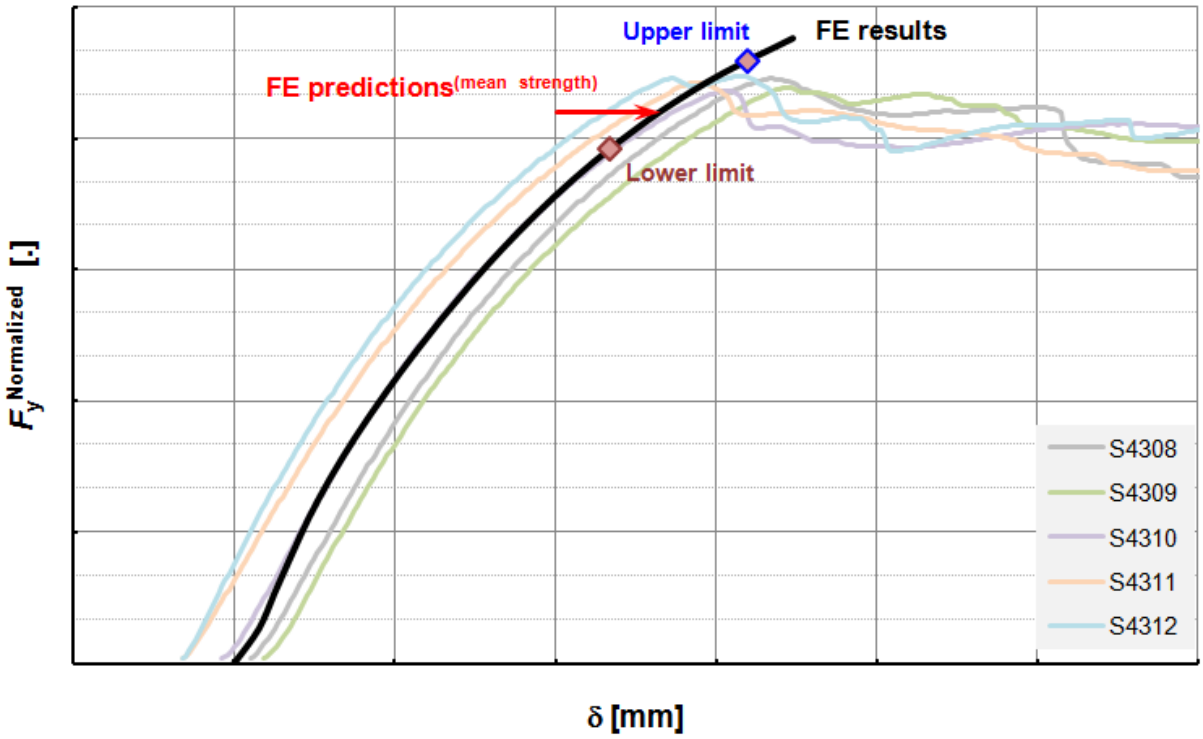

Figure 6: Comparison of the experimental results (the load-displacement response is represented with the transparent solid lines) with the predicted response of the TCP (see the black line) subjected to the lateral crushing load-case for the 2" TCP design. The data is normalized *w.r.t.* the experimental mean. The predicted onset-of-failure based on the delamination strength is also indicated, where the upper and lower limits for the failure are determined based on the governing matrix strength, including the effects of manufacturing imperfections (see the main text).

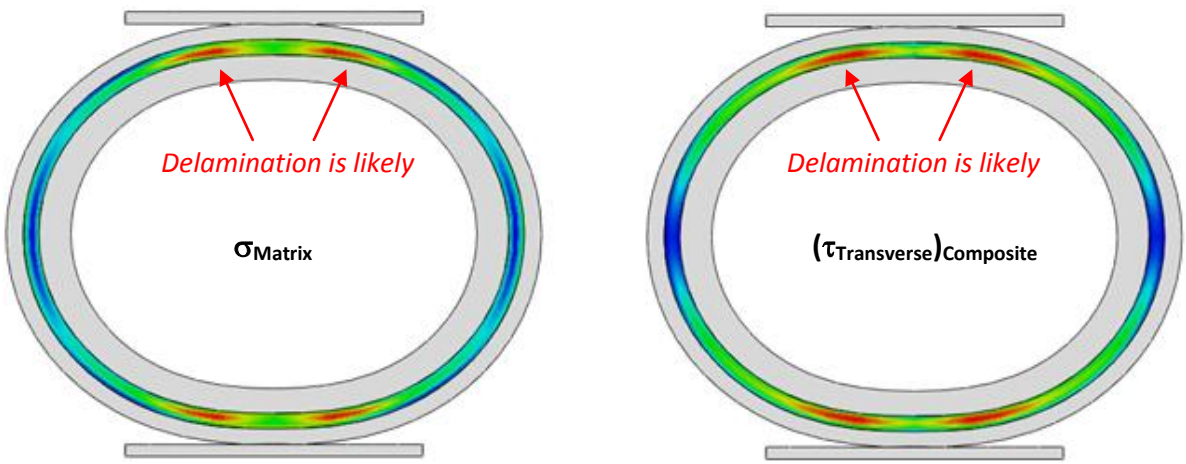

Figure 7: FE results for the 6" (thin-walled) design of the TCP subjected to the lateral crushing load-case. The stress-state within the reinforcement is indicated, where the contour colours represent the stress value with red and blue being the high and low (or zero) values, respectively.

5 SUMMARY AND CONCLUSIONS

The thermoplastic composite pipes (TCP) is a fully-bonded, solid wall pipe with glass or carbon fibre reinforcements completely embedded within the thermoplastic material. The TCP – a lightweight and spoolable composite pipe – is enabling for deeper water exploration, production and intervention, and puts an end to corrosion. Serious efforts have been put into qualification testing according to the qualification pyramid of a very large amount of coupons testing, a moderate amount of mid-size testing (small-scale pipe) and a set of full-scale pipe sample testing mainly for validation purposes. This approach has only been possible with state-of-the-art analysis techniques that can accurately predict the performance of the pipe in the application. One of the more difficult failure mechanisms to predict is the delamination of the pipe, which may result from excessive crushing of the pipe during installation or impact during operations for example.

Delamination is a matrix dominated failure mechanism – however, brittle in nature, which is usually caused by out-of-plane shear stress in the composite lamina. A multi-scale material model of the composite based on the material properties of the constituents (*e.g.*, fibers and matrix) is developed using Digimat and the experimental coupon data. Given a multi-scale material model, delamination is addressed directly at the micro-level (*i.e.*, at the constituents level), where the matrix strength is utilized as the governing strength parameter. Moreover, manufacturing imperfections (*e.g.*, voids) do occur which adversely affect the delamination strength, and are accounted for in the model.

For validation studies, virtual testing of the TCP subjected to the lateral crushing load-case is carried out, where the failure is governed by the delamination of composite layers as observed experimentally. The predicted TCP response is compared with the experimental observations and the onset-of-failure along with the location of delamination are verified. A good correlation has been found between the finite-element predictions and experimental observations. Based on these results the analysis suite of failure mechanisms has been extended to include delamination in the prediction of Airborne TCP for the highly demanding offshore applications.

REFERENCES

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