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Flexible Fiber-reinforced Pipe for 10,000-foot Water Depths: Performance Assessments and Future Challenges

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Abstract

The primary aim of the present composite development program is to enhance access to deepwater fields in the Gulf of Mexico, Brazil, and West Africa. To accomplish that goal, composite materials are being incorporated in unbonded flexible pipelines to lower mass and enhance the overall system performance to expand the operational design envelope. In addition, the use of composite materials will allow a significant improvement in pipe operating pressure (>70 MPa), pipe operating temperature (>125C) and due to increased CO_2 and H_2S resistance, will improve sour service performance and lifespan.

Composite materials are well known for their low density and high specific strength, stiffness and fatigue performance. These properties are desirable and will certainly enhance pipe performance, but the overall performance of the pipe during all stages of manufacture and deployment must be considered, as well as a conservative approach to introducing these new materials. Some of the key factors that need to be assessed are material failure modes under varied pipe loadings, dynamic interactions and exposure to severe oil field environments. There are several individual standards, specifications and joint industry projects (JIPs) focused on composite pipes that address some of these issues, but there is also a general lack of consensus with regard to testing standards and understanding of the long-term performance. As flexible pipe suppliers, the industry must aim to provide performance assessments and address all key challenges to allow the flexible pipe industry to build confidence in the new and enabling composite pipe technologies.

In a previous paper, we presented design concepts and a toolbox approach to construct different composite pipe solutions to meet all the aforementioned performance parameters. The present paper selectively highlights important failure modes and design considerations, demonstrates an understanding of behavior in the matrix and fiber phases, and addresses concerns related to the chemical performance of composite materials. The present paper also highlights and addresses some of the concerns of composite pipes and focuses on areas for future development and testing. These results will support the selection and standardization of analysis tools and testing methods across the industry. Bespoke testing capabilities to address the relevant failure mechanisms and installation strategies for composite pipes will also be discussed.

Introduction

The current program proposes to address the challenge of access to deeper water by hybrid composite pipe solution. Direct replacement of metallic layers with composite materials will often present challenges (1, 9). Metallic materials have been applied as the reinforcement in unbonded flexible pipes since their inception, hence the material behavior, fatigue and failure modes are well understood and documented. The operator's acceptance of qualified testing procedures and adherence to API-17J and DNV codes and recommended practices is also well established. The inherent design methodologies, safety factors and analysis methods are well developed and accepted for metallic materials but will require modification, or at the least, validation whilst working and designing with composite materials.

Composite materials inherently orthotropic in nature and behavior, such as stiffness and fatigue, are relatively well understood at lab scale. However, despite the promised advantages, historically composite materials have been slow in gaining acceptance in structural applications within the oil and gas industry. A reason for this inertia is the lack of unified testing procedures and standards, and concern related to failure models and exposure to harsh chemical environments. In addition, composite materials being composed of two phase, namely matrix and fiber, possess fresh challenges in terms of qualification of these materials.

The current development program has been working with industry partners to develop uniform testing and assessment standards. The present paper addresses some of the general concerns related to the assessment of failure modes, chemical exposure and fiber-matrix interface. It also highlights some of the key testing and installation infrastructure developments to support the manufacture, testing and deployment of the composite pipe. This is the second paper in a series, wherein the first paper discussed in greater depth, the details of the design concept (1).

Summary of the RPSEA programme

In late 2013, GE, with the support of Research Partnership to Secure Energy for America (RPSEA), embarked on a three-phase development program to qualify flexible pipe with an internal diameter of eight inches for ultra-deepwater applications. The statement of work for the first phase primarily focused on the development of a conceptual design to meet the RPSEA objectives for the pipe. In addition, initial material property screening tests were performed to characterize the initial and life limiting behavior of the thermoplastic composite material in the required high pressure, high temperature environment. Lastly, the manufacturability of the thermoplastic composite design was assessed and key process parameters were identified.

The design concept consists of a hybrid composite and metallic/polymer flexible pipe with optimized mass per unit length for ultra-deepwater applications. In the GE design, as shown in Figure 1, the conventional metallic pressure armor is replaced with a carbon fiber reinforced thermoplastic composite pressure armor which is fully bonded to the thermoplastic barrier layer. In an effort to decrease overall programmatic risk and time to realize a qualified product, many of the existing layers and materials remain the same as those used in today's qualified unbonded flexible pipe technology (e.g., the metallic carcass, barrier materials, metallic tensile armor, insulation and sheath). Details of the benefits and challenges of the individual layers of the design concept, as well as the design concept for the pipe's end fittings are described in this report.

To evaluate the conceptual design the RPSEA objectives were translated to appropriate design criteria for working fluid pressures, collapse pressures and fluid temperatures and analyzed with respect to those criteria. In addition, GE worked with its RPSEA working project group to identify a relevant oil field, vessel configuration and metocean data, in an effort to assess the design's performance in a free-hanging catenary configuration. The dynamics of the pipe were determined from those global analyses and were used as the basis for preliminary lifetime/fatigue assessments for the composite pressure armor and are also presented in this report.

To support the design and analysis calculations necessary for the conceptual design, initial mechanical and physical property screening tests of the thermoplastic composite materials were performed. Tensile and compressive properties of the composite lamina were obtained at room and elevated temperatures. The material was also aged at high pressure and temperature to observe the thermo-chemical ageing of the carbon fiber-PVDF material system. Lastly, the team collaborated with Southwest Research Institute to perform the permeation/rapid decompression testing to assess the material's resistance to blistering.

The manufacturability of the design concept was also assessed during the first phase of the program. Because most layers of the design concept remain the same as those of conventional flexible un-bonded pipe, manufacturing facilities already qualified will be utilized for the conventional layers. For the composite layer and its manufacturing process, a new manufacturing process to wrap the composite layers is currently being commissioned. Key process parameters such as winding speed and temperature were identified and their effects on outputs, such as throughput and quality, were identified. An analytical model of the manufacturing processes used to fabricate the composite pressure armor was also created and will continue to be used to optimize the critical process parameters.

To assess and prioritize the risk abatement strategy associated with the composite pipe design concept development effort a comprehensive failure mode, effects and criticality analysis (FMECA) was performed. As the FMECA was built upon existing experience with conventional products, many of the pipe failure modes identified remained the same. As expected, the newly identified failure modes related to the introduction of the composite pressure armor and the failure modes that relate to the adjacent layers. Though there is no current standard for flexible composite pipes, significant guidance on the potential failure modes and mechanisms was leveraged from DNV's standard on composite components.

In the second phase of the program, the technology and manufacturing readiness level of the composite pressure armor will be matured, with focus on the manufacturing and testing of sub-component and prototype pipe constructions. In addition, the development of the manufacturing process line and a substantial parallel program is intended to support the production necessary in the second phase of the program. As noted the FMECA performed during the first phase of the program is used as the basis for prioritizing the tests to be performed under the RPSEA program. Due to the design's incorporation of the conventional metallic carcass, the key tests focus on the burst, bending and fatigue performance of the thermoplastic pressure armor and will be evaluated in both sub-component and prototype testing.

1. Failure Mode Assessment

Figure 1 shows a comparison between conventional metallic reinforcement, unbonded flexible pipe design with the proposed hybrid composite solution. The thermoplastic composite is based on the same polymer as the liner of the pipe enabling a thermoplastic weld to bond the layers. The composite layer is applied with fiber largely in the hoop direction to provide pressure resistance whilst maintaining bending flexibility in the matrix dominated direction. For smaller diameter pipes the composite itself can also provide a degree of collapse resistance, enabling a smoothbore design as shown in Figure 1, but for larger diameters and deepwater, Phase1 of the RPSEA program concluded that a metallic carcass is also required.

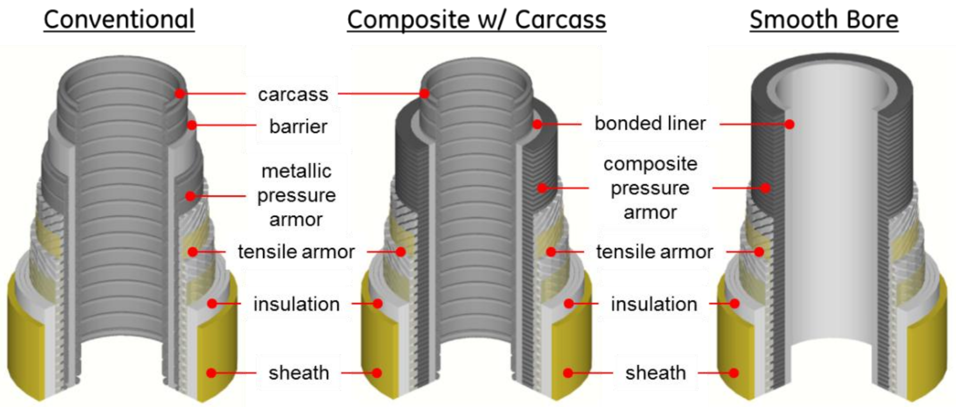

Figure 1. Comparison of typical flexible pipe -v- proposed hybrid solution

It is acknowledged that current available testing and qualification standards do not fully account for the above proposed changes and there is an industry-wide effort to develop performance data and new design practices (2-6). As discussed, the presence of a bonded composite layer results in changes in design and potential failure modes; the stiffness of the overall pipe structure increases affecting the minimum bend radius. However, this is offset by the requirement of a thinner composite hoop layer when compared like for like with the metallic Flexlok™ layer.

Though there are several failure modes, one of the most important failure modes for fiber reinforced composite materials is in compression. The composite layer within the hybrid pipe structure can experience compressive loads from, for example, global pipe loading due to external hydrostatic pressure (collapse load), bending or local interlayer interactions (metallic tensile armor). Figure 2 shows the development of a crack under a compressive load in a ring specimen cut from a pipe, which was captured and imaged using 3D X-ray tomography. The ring sample was loaded between two parallel plates to study this failure mode. The initiation of the crack is believed to be sub-surface and is only noticeable visibly when there is a resulting local buckling of the fibers out of the surface. The defect then propagates by delamination between the composite layers as the load is increased. Work is in progress under RPSEA phase 2 and internal supporting efforts to further define critical failure modes and their relevance to the global and local pipe load cases, the aim being to quantify the critical defect sizes and the design safety factors for static and fatigue loading for the composite layer.

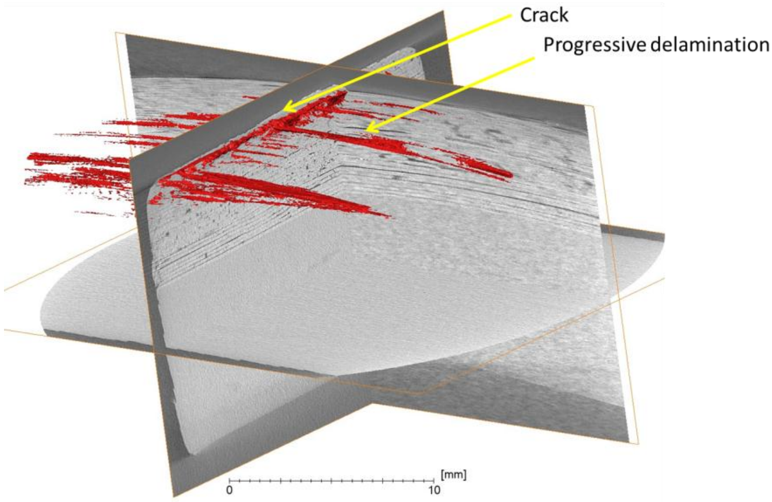

Figure 2. 3D CT scanning and detection of crack in composite specimen

Composites are anisotropic when compared to metallic structures, having significantly different behavior in tension and compression. Under tension metallic structures are generally designed to operate in the linear region of their stress strain curve and ultimately yielding is the precursor of failure. However, composites, in the fiber dominated direction, are almost entirely elastic with no yield before failure. The present work demonstrates an appreciation for the different failure modes of the composite layer when compared to a metallic structure. In an effort to better address these concerns and align testing resources and priorities the present program has carried out a detailed FMECA with the help of operators and third party certification to prioritise the testing matrix.

Some concerns related to the fiber matrix interface and ageing have already been addressed. This is discussed in the following sections based on phase 1 RPSEA work. Additionally, some key tests have been highlighted which are due to be addressed in phases 2 and 3.

2. Understanding of Matrix and Filler Property and Interlayer Interaction

Conventional flexible pipe industry (metallic/polymer) has been in existence for more than 30 years. These pipes use a range of thermoplastic polymers based on field conditions. Thermoplastic polymers are non-linear in their behavior and compared to reinforcing fiber such as carbon or glass. Composite by definition is a combination of matrix and fibers. However, the way to combine these is based on industry and application. GE Aviation's business uses composite by optimizing high fiber content and low matrix content to keep the fiber together and focuses on the stiffness of the structure, its strength and impact resistance. However, GE Oil & Gas uses composite by utilizing high matrix content and fiber providing only required reinforcement. This approach enables us to push design boundaries and utilize high fiber strength for hoop resistance, whilst maintaining the non-linear behavior of the matrix for flexibility of the pipe.

From decades of experience with PVDF, PA-12 and HDPE, a comprehensive understanding of the thermoplastic matrix (7, 10 & 11) is well understood. This includes understanding of ageing, fatigue and chemical exposure. Using this approach leads to an obvious focus on additional components making up the composite i.e, matrix filler interface and fiber used for reinforcement.

Multiscale modelling utilizes inputs, both from a nonlinear thermoplastic matrix and carbon fiber enabling visualization of stresses in both the carbon and matrix phases. Figure 3 shows these stresses in the carbon and matrix phases. A multiscale modelling approach enables modelling of fiber dependent properties (such as hoop resistance) and matrix dependent properties (fatigue) more accurately and correctly.

A separate issue is the interaction of the metallic layers with the wound composite hoop layer. Images of the finite element model used to study this interaction are shown in Figure 4. It is important to understand the behavior of the whole structure under different load cases and temperatures to ensure the limit of design and structure. Various layers have also been designed to ensure the addition of the composite layer does not reduce the chemical resistance performance. The proposed design of various layers ensures the issue, such as the galvanic corrosion set-up between the fiber layer and the metallic layer, have been taken in account.

In addition, the presence of the continuous composite wound layer ensures that problems associated with creep of a barrier in conventional metallic Flexlok designs are eliminated. However, an interaction between the composite layers and an intermediate layer with the metallic tensile armor layer is present. It should be noted that the presence of fiber in the composite matrix should minimize, if not eliminate, any such related creep issues (10).

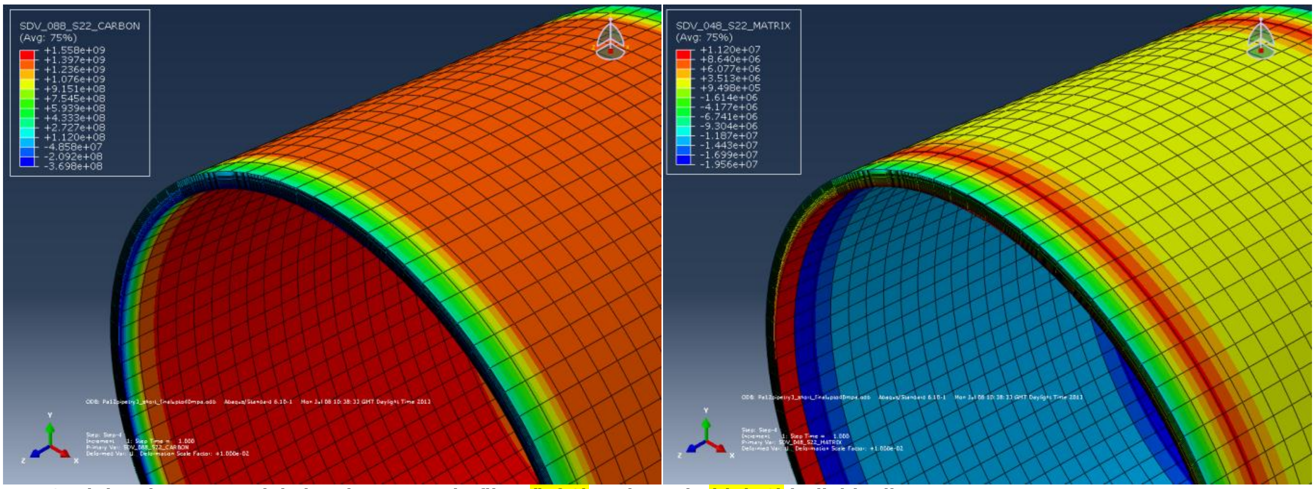

Figure 3. Finite element model showing stress in fiber (left?) and matrix (right?) individually

Figure 4. Finite element model used to study composite - metallic layer interactions

3. Effect of Chemical Exposure and the Importance of Matrix Filler Interface

A typical bore environment for two different pipes is shown in Table 1. It is important to assess the effect of the chemical environment on the composite layer. Table 1 shows how the composite layer would be exposed to varying levels of CO_2 CH_4 and H_2S. As discussed, it is important to understand the effect of these on the matrix, matrix fiber interface and fiber. It is also important to understand the stress generated due to swelling of the matrix and how these stresses compare with the interfacial strength between fiber and matrix.

Table 1. Components of typical chemical environments

Parameter	Environment 1	Environment 2
Temperature/°C	**50**	**125**
Pressure/bar	400	400
CO_2/%	90	88.44
CH_4/%	10	10.79
H_2S/%		0.00360%
Water/moisture	Vary	Vary
$_P$H	4-5	4-5
RDG rate bar/min	70	70

To address the thermo-chemical effects in the composite material, CheFEM, which is based on Sanchez-Lacombe Equation of State for solubility and swelling calculations, extended with inclusions for crystallinity, glass temperature transition and crosslink pressure was used. Figure 4 shows the chemical potential generated due to CO_2 permeation in the composite. Percentage permeation level differs in the composite and polymer phase. The composite is restrained by the fiber, hence overall swelling is reduced. However, local swelling stresses are greater in the composite matrix. If these stresses are kept lower than the interfacial fiber matrix energy then the composite matrix will avoid micro-cracking, blistering or debonding. A typical comparison is shown in Figure 5.

It is also important to understand chemical degradation; in the present case the equilibrium constant (K_{eq}) and molar concentration of the reactive groups of a specific substrate have been determined using a suitable experiment. An estimation of chemical degradation was made and compared with experimental values to ensure there is no detrimental impact on mechanical performance.

The matrix response to rapid gas decompression is defined using the previously-determined swelling and diffusion data in combination with a uniaxial stress analysis; an example is shown in Figure 5. It is important to take into account the stress generated during rapid gas decompression in the overall design of the pipe or localised buckling or voids formation may occur with blistering.

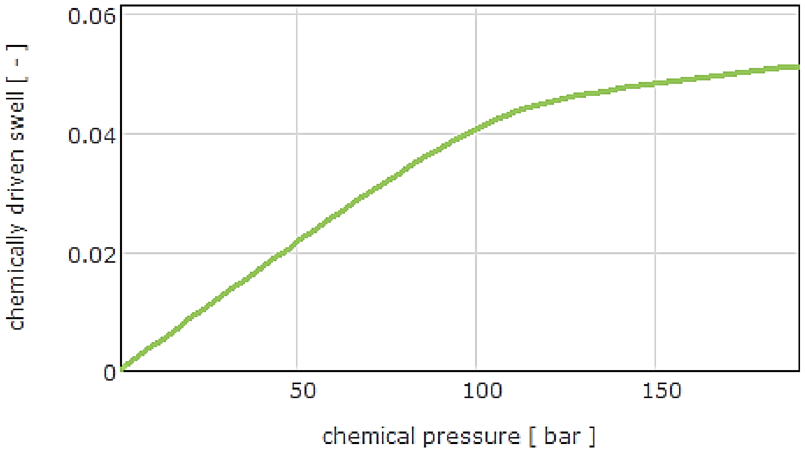

Figure 4. Swelling simulation for CO_2 in carbon reinforced composite

Table 2. Example of prediction of swelling stress and chemical reaction in composite

Swelling Stress		Chemical Reaction	
Swelling	Matrix-filler Restraint	Conversion	Max Void Pressure
7 MPa	21 MPa	1.43%	199 bar

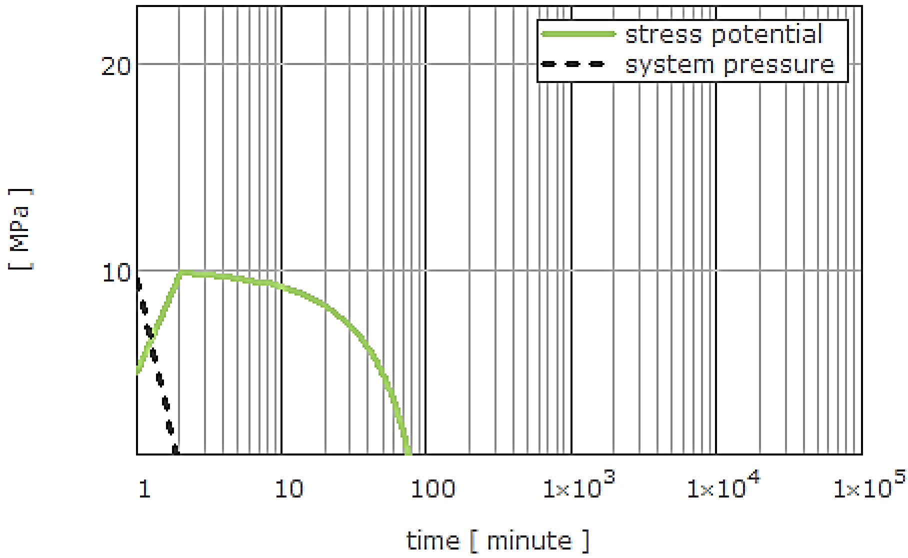

Figure 5. CO_2 decompression from 190 bar to 1 bar in 2 minutes. Initial swelling in thickness direction: 7%

4. Future Challenges, Concerns and Approach of Performance Analysis

Composite materials offer high fatigue resistance. However, it is important to understand and characterise fatigue and environmental fatigue. This assessment is designed to ensure that the matrix, fiber and matrix-fiber interface maintain their integrity throughout the lifetime of the composite layer. Based on FMECA and global analysis the critical loading conditions determined were tension (representing hoop fatigue), bending fatigue and thermal cycling. To assess those aspects the program has developed bespoke test rigs capable of evaluating the loading conditions over a range of temperatures and pressures. For example, Figure 6 presents a standard bending fatigue test fixture, which has been modified to allow testing in controlled environments at a range of temperatures. Similarly, Figure 7 presents an image of a pipe bending fatigue test rig that allows fully-reversing strain fatigue to be evaluated in a controlled thermal environment. Figure 8 displays a thermal temperature map of the viscoelastic heat dissipation from the pipe during midscale bend fatigue testing.

GE Oil & Gas will also focus on understanding the effect of combined loading on the performance of pipes. Combined loading conditions considered critical are combined bend collapse, bend fatigue, bend-burst and thermal mechanical loading. GE Oil & gas have a bespoke rig to perform these tests, some of which are highlighted here and were discussed in the earlier paper.

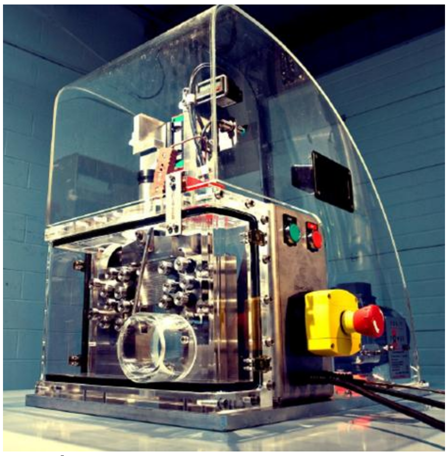

Figure 6. Lab scale bend fatigue under varying enviorments

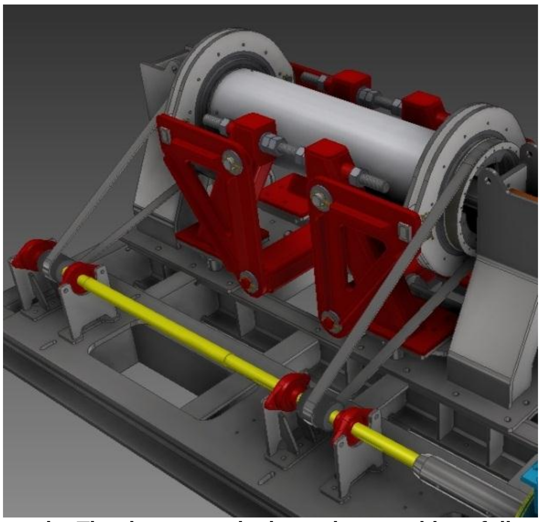

Figure 7. A CAD image of the bending fatigue rig. The rig rotates the bent pipe to achieve fully-reversing bending strains

As discussed, Figure 8 highlights the typical warming up of a thermoplastic pipe, which is viscoelastic in nature, in bending fatigue. This phenomenon is different when compared to a thermosetting matrix, currently being evaluated by other companies. A thermosetting matrix tends to have initial elastic behavior followed by a sudden brittle failure. It does have a mechanism for viscous heat dissipation hence, disadvantages associated with them reduces their performance envelope.

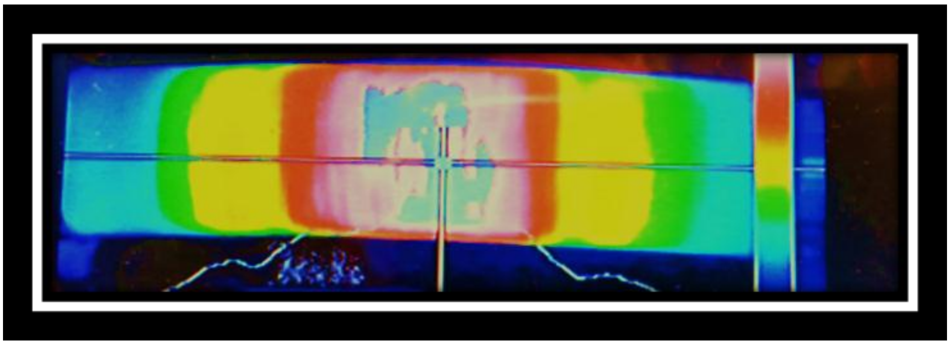

Figure 8. Heat generation in the thermoplastic matrix captured during bend fatigue testing at high rotational speed

5. Storage and Installation for Hybrid Composite Pipes

To support the larger diameter composite pipe configurations, the current development program has invested in a new carousel building, housing two 26 m diameter, 3,000 tonne manufacturing and storage carousels, adding to the existing 2,000 tonne capacity. The investment in this expansion allows the manufacture of longer lengths and larger diameters of flexible pipelines for bigger remote offshore developments with reduced mid-line connections, end fittings, leaders and trailers, thereby reducing installation costs.

As the hybrid construction composite pipe will be lighter in design and longer in length, the design has been optimised to match weight and buoyancy to eliminate or reduce the use of buoyancy or ancillaries used during installation. In addition, an appropriate installation procedure is being developed to minimize the crush, impact and compressive loads which can affect the integrity or performance of the composite layer.

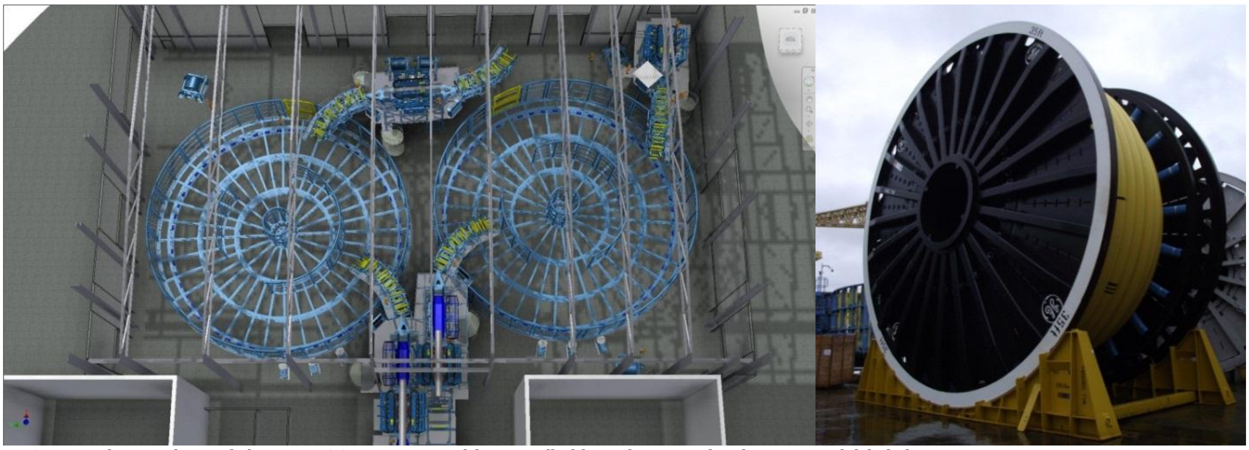

Figure 10. Top-down view of the new 26-m carousel layout (left) and a standard 4.4m reel (right)

Conclusion

The future of composite pipe depends on detailed assessment of failure modes. GE Oil & Gas have reviewed various failure modes and discussed various methods for detailed performance assessments. However, further work is required to develop uniform testing standards and develop customer acceptability for these standards.

The present paper highlights the significant differences of composites from metallic materials and their usage would require modification of current testing methods and standards. Understanding of the behavior matrix and fiber is important as they combine to give the performance of composites as a single unit. Chemical exposure and its effect on fiber–matrix interface is also important as it can affect the performance of composite layers. FMECA has been used to prioritise key future tests. Future challenges have been highlighted here and GE Oil & Gas continues to address all of the above.

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