COMPOSITE MATERIALS FOR OFFSHORE OPERATIONS – 4

The Development and Validation of a High Strength, Self Monitoring, Composite, Tight Fit Liner for Offshore Pipelines and Risers

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ABSTRACT

By its insertion as a tight fitting liner, the concept introduced in this paper provides an attractive alternative for the rehabilitation of degraded steel pipe and risers in offshore applications. It offers three significant advantages. First, the use of ultra high strength polymer fiber composite materials enables high pressures, bending resistance, impact protection, and internal corrosion protection with minimal reductions in product flow. Second, by the use of integrated fiber optics sensing systems, continuous, non intrusive monitoring (i.e., point by point measurement of strain and temperature) of its condition is provided throughout its service life. Third, it can be tailored for any particular operating conditions, and can be constructed and simultaneously inserted into a degraded host pipe in a long continuous piece, thus eliminating most in-field joining operations. However, because the concept is a composite of thermoplastic materials, its design, manufacturing, installation, and qualification procedures are much more demanding than for more conventional materials. To meet the challenges that are posed by viscoelastic behavior of the components of the composite, analysis and experimental research has been addressed to determining the strength, flexibility, and long term durability of ultra high strength fibers. These fibers, which are generally used for ballistic applications, have elastic moduli that are comparable to those of steel, but are considerably stronger and lighter. Following brief background reviews of the design, manufacturing, installation and in-service monitoring procedures associated with this concept, this paper provides current progress in on-going research aimed at quantifying the strength and durability of high performance polyethylene fibers in very long term liner service.

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INTRODUCTION

This paper will present information relative to the development of Smart Pipe® a stand alone Reinforced Thermoplastic Pipe (RTP) tight-fit pipe liner in accordance with API Recommended Practice (RP) 15S. This product is a continuously manufactured, high strength, light weight, durable, self monitoring, composite material that can be used as a stand alone pipe for various offshore applications, or inserted as a tight fitting liner to rehabilitate an existing steel pipe or a riser. The technology has evolved from a combination of flexible pipe, RTP, and fold and form processes. The major advantages of the concept are:

- its composite of ultra high strength thermoplastic materials permits high pressures, internal corrosion protection, impact damage mitigation, and minimal flow resistance.
- its continuous 24/7 monitoring feature enables leaks, mechanical impacts, and major movements to be instantaneously detected all along the line throughout its service.
- its integrated sensor system provides an on demand inspection report that has the potential to eliminate smart pigging and hydro testing.
- its installation can be made in very long, continuous lengths, thus eliminating most in-field joining operations.
- its annular venting system allows permeated gases to be removed thus preventing any damaging pressure build up.

It is also the only high pressure tight-fit lining product that conforms to the requirements of the recently approved API RP 15S, <u>Qualification of Spoolable Composite Pipe</u> that can be inserted in a very long host pipe.

However, as compelling as the mechanical properties of ultra high strength fiber composite materials are, their use makes the design and installation procedures much more demanding than they are for more conventional materials. Pipeline layouts can be highly complex (e.g., sharp bends, elevation changes), exacerbating the sensitivity of composite materials to stress concentrations and large deformations. More importantly, all thermoplastic load bearing elements exhibit some degree of creep behavior. Given the very long expected durations of their use in offshore installations (e.g., 40 years of continual load bearing), the potential for creep, however slight, is a significant challenge to the long term durability of the composite.

As discussed in this paper, research using engineering models, finite element analyses, and laboratory and full scale experiments, is being performed to support the development of this product. This research has in particular led to an improved quantitative understanding of the effects of the viscoelasticity of ultra high strength fibers in pipeline and offshore applications. This understanding is, in turn, permitting the desirable properties of these materials to be effectively utilized without jeopardizing their long term performance. In the following, along with brief descriptions of the design, manufacturing, installation, and in-service monitoring procedures that are given for background purposes, the research that is currently being performed for this product to quantify the strength and the long term durability of ultra high strength composites will be outlined.

BACKGROUND

The Smart Pipe$^{®}$ concept shown in Figure 1 centers on a monitorable pipe liner that is a composite of various thermoplastic materials in monolithic and fibrous form. The liner is manufactured in a portable factory that starts with a polyethylene core pipe upon which a combination of longitudinal and co-helically wrapped fabrics, tapes and tows made of ultra high strength fibers [1], and fiber optic sensors, are positioned in stages. After being encased with a thin outer protective layer, the liner material is deformed into a "C" shape for insertion into a host pipe or riser. After being pulled into the host pipe, it is reformed into a tight fitting liner that is capable of sustaining very high internal pressures, external impacts, and bending stresses, while permitting continual condition monitoring.

The Portable Factory

One of the many unique features of this concept is the ability to transport the factory to a convenient location relative to a job site. When located right at a job site, the product can be simultaneously manufactured and installed. For offshore installations, the factory can be moved to a position where the liner can be produced and loaded on barged-based carousels that can be taken offshore. In either instance, the portable factory functions in the same general manner. The portable factory is approximately 500 ft in length, and consists of ten separate stations that are controlled by an integrated software control system.

The factory is mounted on interlocking polyethylene matting. For the machines that require periodic reloading of fabrics, a motorized track system is employed. These machines are reloaded while running in a "keep up" mode such that the new fabric is spooled and spliced while the line is continuously moving. Upon completion of that operation the machines restart at the same point and angle to ensure consistency of the fabric winding. By utilizing customized tenting and air moving systems, the factory has a climate controlled environment that ensures that the manufacturing is done at a near constant temperature. There is also a climate controlled area that is used for storage and QA/QC checks on the component materials prior to the manufacturing.

Common to all stations in the portable factory are emergency shut down systems that can be activated by an operator or by the control room. Each station incorporates state of the art quality control in accordance with ISO 9001:2000 standards. The factory operators are all multi-disciplined in the operations of each machine and each station such that crew sizes can be kept to a minimum of approximately 12 operators per shift on 12 hour shifts.

The Liner Construction

The proprietary technology for the construction of the liner, shown in completed form in Figure 1, begins with a butt fusion welding machine that welds sections of the core pipe while traveling along a track section, Figure 2. The welds are ultrasonically inspected by a time-of-flight-diffraction system. The length of track and welding times are synchronized such that an improper weld can be cut out, re-welded, and re-inspected without changing the speed of the manufacturing line.

The next station consists of machines that wrap the ultra high strength fiber fabrics helically and counter helically onto the core pipe. The station that follows places several carbon pulling tapes and fiber optic sensors in the axial direction, equidistant around the circumference. Orbital winding machines then lay down co-helical tows of ultra high strength fibers, to hold the carbon fiber tapes and fiber optic sensors in place, Figure 3.

The outer wrapper station that follows consists of a machine that pulls an HDPE sheet into the forming section, Figure 4. The forming section wraps the HDPE sheet around the liner as it is pulled through the machine. A single seam weld is made before the liner enters the prime mover. The prime mover is a catapuller mechanism that grips the pipe with a controlled pneumatic system that pulls the liner material through all stations. The prime mover, which sets the running speed of the portable factory, is completely automated to maintain and manufacture a consistent product. It is currently designed to produce at least one mile of product per day (24 hrs).

The final step in the manufacturing process is a folding machine with a complex system of rollers and hydraulic controls that mechanically transform the round pipe into a "C" shape. The "C" forming process reduces the apparent circumference by a factor of 2 which permit the easy installation of the liner into an existing pipe. A proprietary process is used to maintain the C shape during installation and to allow the reformation upon demand. A buffer catapuller -- a machine that is a two belted catapuller -- provides a pulling force to the pipe as it runs through the previous machine, Figure 5.

The Installation Procedure

The installation begins with the preparatory flushing and cleaning of the existing pipeline. During this operation a small diameter tag line is placed in the pipeline pulled behind an umbrella or a poly pig. This tag line is then connected to the large diameter pulling rope and pulled to the beginning of the pipeline.

The large diameter polyethylene pulling rope is attached to the product and pulled into place using a high tension traction winch in lengths up to 10 miles. There are two types of connectors, both based on the same engineering concept, Figure 6. Specifically, a pulling head weaves the carbon fiber tapes into a rope and is spliced to the pulling rope. The end connector is a trap lock system that goes back to flanged connection to hook up to existing flange on host pipe. The pulling rope (plasma 12 strand rope) is the highest strength synthetic rope available. The rope is manufactured with Honeywell Spectra® fibers that have been enhanced by the Puget Sound Rope Company's patented "plasma" process. It should be noted that this will be the longest continuous rope ever manufactured.

Once the product has been properly positioned within the host pipe, expansion heads are attached to both ends of the liner and pressure is applied to expand the product to a tight fit within the host pipe. The product is the trimmed to length and flanged to the host pipe. The final steps of installation include a poly pig run to ensure full reforming of the product, a hydrotest, and the installation of spool pieces to conclude the pipeline continuity.

The Monitoring System

The optical fiber monitoring system is a field proven system developed by Smartec S/A of Switzerland, and described in their paper for this conference [2]. More than 60 systems have been installed and are being successfully used to monitor several long pipelines and structures in various locations. It consists of three (or more) “SmartProfile” cables that are placed over the reinforcement fabric and, a reading instrument and system software. Each of the three SmartProfile cables, which are distributed uniformly around the circumference, has multiple optical fibers for redundancy. The fibers are enclosed in a gel filled tube with at least one optical fiber on each side of the tube. The optical fibers in the gel measure temperature changes without being influenced by strain. The optical fibers mounted adjacent to the tube respond to strains in the tight fit liner.

Measurements using both sets of optical fibers are based on a Brillouin technique that allows measurements of small changes over great lengths. The temperature measurement has been demonstrated to show that it can detect even minimal sized leaks in the pipe wall. The temperature measurement has a resolution of 1 ^{0}C at any point along a 17-km (10-mile) pipeline, while the strain measurements, which also use the Brillouin technique, have a resolution of 20 micro-strains over the same distance. In addition, using a concept similar to optical time domain reflectometry, any measured value can be located within +- .5 meter (1.6-feet) over a 17-km (10-mile) pipeline. The monitoring capability is designed for periodic monitoring, remote monitoring, or monitoring on a 24/7 basis using anomaly alarms set on the basis of test data and a baseline measurement established after the installation of the liner.

Annular Venting System

The product includes continuous axial channels for the collection and accumulation of permeated gases. These channels are cross connected to a port at each end of the pipeline to permit bleeding or vacuuming of gases, thus preventing any damaging pressure build up.

Material Selection

Materials have been selected on the basis of their mechanical and chemical resistance properties, with strength to weight ratio also being a driver. As currently envisioned, the primary materials used for the various constituents shown in Figure 1 are as follows:

Core Pipe. PE-100 is used for the core pipe that is the inner portion of the liner. This material, which has been extensively used in oilfield environments, offers superior resistance to creep rupture, stress cracking and rapid crack growth than conventional HDPE materials. While the inner liner is primarily a pressure barrier and not a strength member, it must be strong and durable enough to maintain its pressure barrier. It is provided with ultraviolet light protection using a white or other light reflective color to facilitate the use of video cameras during installation, or in any supplemental in-line inspections that might be desirable.

Primary Reinforcement. The most attractive of a number of candidate ultra high strength fibers that could be used in fabric/tape as the primary reinforcements are the class of Honeywell Spectra® Performance Fibers. Of the known commercially and relatively available fiber materials presented in Table 1, Spectra® has the best strength to density ratio. While other choices of fiber can be made that might better suit the conditions of a specific installation, because of its superior durability in long term service, initial installations will use a hybrid of Spectra® 1000 with carbon fibers. These fibers can be woven into a balanced fabric and encapsulated in a thermoplastic material for added stability and ease of handling.

Axial Tapes. Carbon fiber is used for the axial fiber tapes primarily for its high stiffness, generally availability, and reasonable strength to weight ratio. These tapes are processed with a proprietary technique that provides additional stability and ease of handling. These tapes are sized to provide 100% of the axial pulling force required during the installation of a liner.

Tows. The size and number of tows used is usually selected to provide an open pattern, although full coverage can be used when additional reinforcement is needed.

Cover – Wear Jacket. The cover or wear jacket protects the product during installation is a light weight high strength, wear and impact resistant polymer. Prototype testing is also being conducted to evaluate the effectives of a spray on material that cures rapidly.

Verification Testing

Substantial qualification testing on the forming and reforming of HDPE pipe has been conducted by Tulane University [3]. These very positive data strongly indicate that the most vulnerable component in the composite can safely withstand the C-forming process. Similarly, the annular venting system was successfully tested by the pipeline industry with the results being presented in the NACE corrosion 2000 symposium in paper 00784 [4].

Qualification testing of the product's long term pressure rating will be done in accordance with Paragraph 5 of the API Recommended Practice (RP) for the Qualification of Spoolable Reinforced Plastic Line Pipe. This performance based document specifies that the pressure and temperature rating be determined by a series of stress rupture tests under constant pressure at the qualification test temperature. The testing procedure is described in ASTM D2992 – Procedure B and requires a minimum of 18-failure points in the range from 10 to more than 10,000-hours. Testing includes the primary connection means and serves to qualify the connector, as well as the product. The failure points are used to establish a mean long term hydrostatic pressure regression line.

STRENGTH AND DURABILITY ANALYSES

Engineering and finite element stress analysis models have been developed that are used to design a liner material for pressure-induced stress in both quasi-static and creep conditions. Finite element analysis (FEA) models have also been developed and utilized for the large deformation conditions that are encountered in the C-forming process and during installation. An outline of these approaches is provided in this section.

Elastic Strength Analyses

There are two primary equations used in the design of a liner for a particular installation. These are for the specified maximum burst pressure, p_{max} , and the maximum pull-in length that will be encountered, L_{max}. Basic engineering models are used to scope the construction (i.e., fiber types and amounts, wrap angle) that will meet the specifications. The most challenging loading conditions are those arising in a hydrostatic proof test where both hoop and axial direction pressure–induced forces occur. Because no credit is taken for the presence of a host pipe, in essence, the product is designed as a stand alone pipe.

Because the weight of the product per unit length is a function of the amounts and densities of the fabrics and the tapes, for any angle θ, these two equations must be solved simultaneously to determine the main design parameters for any selected combination of fiber materials. The selection of θ is constrained by the need for the combination of the co-helical fabrics and the axial tapes to have the combined strength needed to resist the axial direction pressure-induced stresses. For installations requiring pull-in lengths of several miles, the amount of axial direction fibers required for the pull-in will generally suffice to carry the entire axial direction pressure force. In this case, which is generally expected to occur, the co-helical wrap angle θ can be set as near to 90^o as is practical in order to minimize the number of ends needed for a given burst pressure.

However, for a short pull-in length, the contribution of the axial fibers must be supplemented by the co-helical fabrics, whereupon θ can be only modestly above 55^o, the equilibrium angle for a pair of co-helically wrapped fabrics acting alone; i.e., the natural angle. Example calculated results for a liner in which the pull-in length would not suffice to eliminate the need for the co-helical fabrics to carry some of the axial force in a hydrotest are shown in Figure 7.

The calculations shown in Figure 7 were made for a liner with co-helically wrapped fabric having properties comparable to Spectra® 1000 and with axial tape of carbon fibers. The minor contributions of the HDPE core, the tows, and other components of the liner were not considered. It can be seen that there is an optimum wrap angle. At angles higher than the optimum it is the failure of the axial tapes that will cause failure. Note that the while the natural angle is relatively insensitive to the amounts of fabric and tape, the optimum angle (i.e., the angle at which the failure point of the co-helical fabrics is just equal to the failure point of the axial tapes), is strongly dependent on these quantities, and will therefore differ from one application to another.

Classical composites theory is not directly applicable to Smart Pipe® designs because no matrix materials are used. The key effect of the absence of a matrix is that the helical fibers will tend to seek out their natural wrap angle unless prevented. To address this and other complications that cannot be included in a basic engineering model, a more accurate spreadsheet model has also been developed. Figure 7 shows that, at least for the parameters used in this example, the basic model will suffice for preliminary scoping purposes, a conclusion that is reinforced by FEA solutions that are also provided in figure 7.

In conditions where engineering models cannot be expected to be reliable, FEA methodology has been used. For burst pressure analyses, it is possible to include the nonlinear stress-strain behavior of the HDPE as well as the contribution of the helical tows. More importantly, FEA was also used to analyze the large scale deformation process in C-forming where a finished liner is reduced from a circular cross section to a C shaped cross section. This work has demonstrated that the C-forming will not damage the liner, and, by providing the contact forces of the deformation process, it has also effectively guided the design of the C-former apparatus. Other FEA work has directed at quantifying the minimum bend radii and bend angles that can be safely encountered in an installation.

Viscoelastic Durability Analyses

While the time-independent mechanical properties of ultra high strength fibers shown in Table 1 are more than satisfactory, all of these currently available fibers appear to exhibit some degree of time and temperature dependence. This is particularly a challenge in fibers, which otherwise present the best combination of strength to weight. Creep and creep rupture is a particular challenge for pipelines where the operating duration is considerably greater than in most other applications. To scope this challenge viscoelastic analyses were made using the properties of a representative member of the class of high performance polyethylene (HPPE) fibers

A substantial amount of data exists that demonstrates that HPPE fibers will creep under constant load at all potential service temperatures. While many of these data sets are proprietary, others are available in the open literature [5-8]. For high strength rope applications, where the efficiency factors are 0.5 or less and factors of safety of commonly at least 5, these effects combine to assure that the service stresses are not greater than 10% of the ultimate strength of the fibers. In this range, the creep data are well represented by the linear viscoelastic relation drawn from the four parameter fluid model, whereupon the load superposition through a hereditary integral is possible [9]. This enables the entire stress history of the rope to be taken into account during a pull-in operation.

The linear viscoelastic results demonstrate that, even for HPPE fibers that behave in the manner of a viscoelastic fluid, a large (but not unlimited) number of repeated uses appear to be possible without jeopardizing the operation. Moreover, if the rope is reversed from one pull to another, because the highest stressed points in one installation will become the least stressed in the next, the safe operating life of the a rope can be doubled. This and other techniques that are part of a rope management methodology based on viscoelastic modeling can be used to achieve a balance between long term usage and the reliability of the rope.

In comparison to the load levels and durations that are experienced by the HPPE fibers in a high strength rope during a pull-in operation (or most other known applications), the loads and load durations in a rehabilitation of a degraded pipe are much more demanding. Particularly in view of the load levels experienced by a liner, recognition of the nonlinear (in regard to stress) behavior of the HPPE material is essential. Based on the available (open literature and proprietary) databases for these materials, the creep behavior under constant applied stress is well expressed in an empirical adaptation of the four parameter fluid model.

This nonlinear viscoelastic relationship indicates that a product made of HPPE fibers could be susceptible to premature creep rupture. While this finding mitigates against the use of these fibers, it is still possible to benefit from their desirable properties by pairing them with time-independent fibers in the form of a hybrid [6]. For a hybrid of carbon and HPPE fibers as the reinforcement material, the strain history of the hybrid can be calculated by allowing the HPPE fibers to creep while the carbon fibers remain elastic. Because the two sets of fibers must have the same strain, the load will be continually redistributed, with the result being that the hybrid will achieve a plateau strain. An example calculated result for a hybrid with 70% HPPE fibers and 30% carbon fibers showing this is given in Figure 8.

The results shown in figure 8 indicate that HPPE/carbon hybrids can be durable even for the very long term service lives that the product must achieve in offshore applications. Moreover, in addition to giving a large margin of safety in the critical early stages of service, the HPPE will be present to “cushion” the fabric against mechanical impacts and shock loadings through out the life of the hybrid. A form of hybrid material is to be used in the current Smart Pipe® design, assuring both the ability to carry large pressures and long term durability of an installation.

CONCLUDING REMARKS

The tight fitting liner (Smart Pipe®) concept presented in this paper represents a unique combination of several unique elements. It can be constructed in a large range of diameters to hold very high internal pressures, and it embodies a continuous self-monitoring system that can near instantaneously detect pipeline movements, seismic activity, near disturbances, impacts and leaks. The portable factory allows long installation lengths without a need for in-field joining. Since its inception, the concept has been primarily focused on aging and degraded, on-land, energy transmission pipelines. However, it is sufficiently versatile that it can also be readily used for the rehabilitation of pipelines, risers and other structural components in offshore applications. Factory development and product manufacturing have been completed with field trials underway. Having successfully demonstrated the veracity of the concept for on-land pipelines, with minor modifications, it is expected that it will become available for offshore applications. The product will provide an economical and reliable alternative to, loading hose, risers, and light weight facility piping. This product will also allow the reuse of existing pipeline infrastructures which in turn eliminates the need for digging canals in wetlands for new pipelines that leads to coastal erosion.

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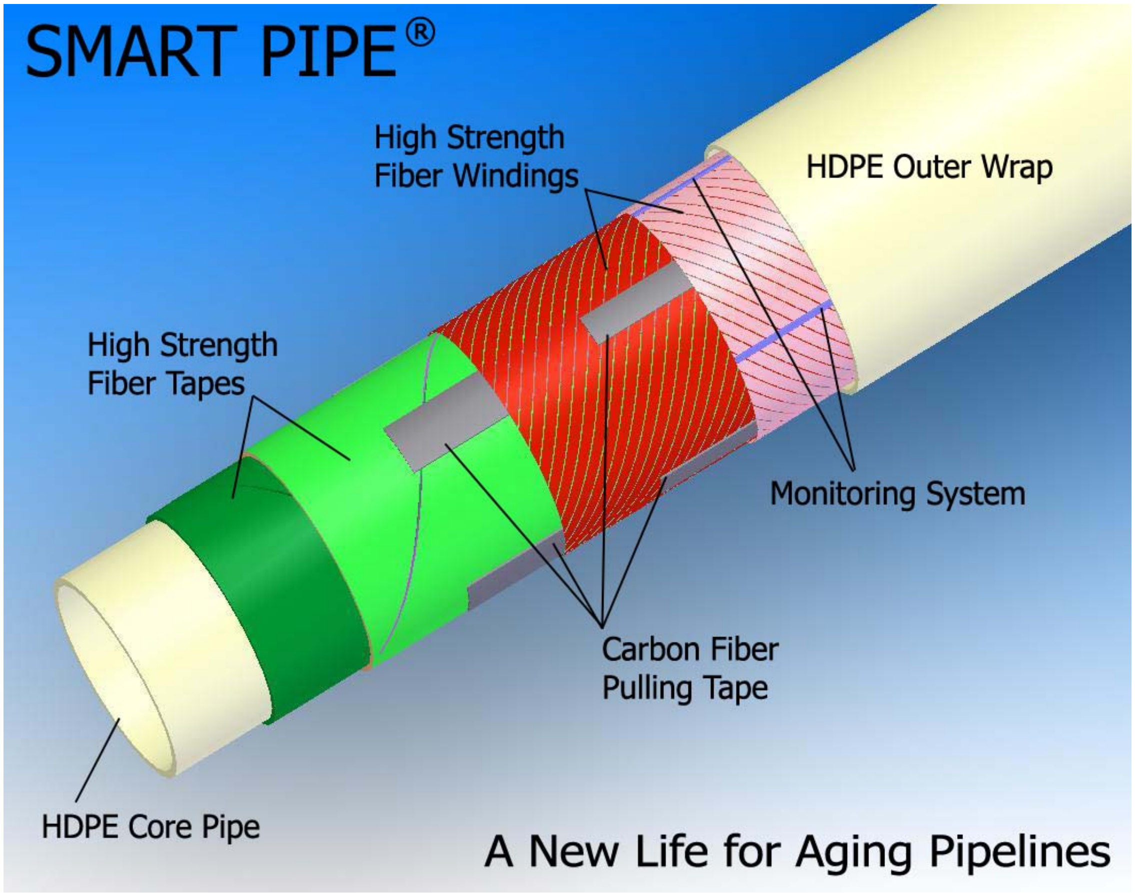
Table 1: Mechanical Properties of Representative Ultra High Strength Fiber Materials

Fiber Type	Measured Mechanical Properties Density (lbs/in^3)	Modulus (ksi)	Strength (ksi)	Calculated Strength Density Ratio (miles)
M5®	.061	43,000	1200	310
Spectra®	.035	15,000	435	196
Carbon	.065	34,000	700	170
Kevlar®	.052	18,000	525	159
Vectran®	.050	9,000	412	130
E-Glass	.092	12,000	500	86
Pipe Steel	.283	29,000	100	6



Patent Pending

Figure 1.- Schematic View of Smart Pipe® Construction

Figure 2. - Welding the HDPE Core Pipe

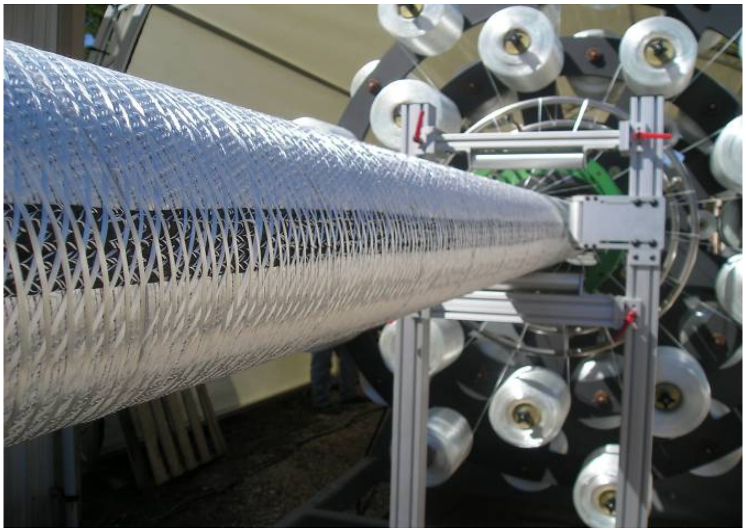


Figure 3. - Axial Carbon Tapes and Tows

Figure 4.-The Portable Factory with Near Complete Product

Figure 5.-The Caterpuller

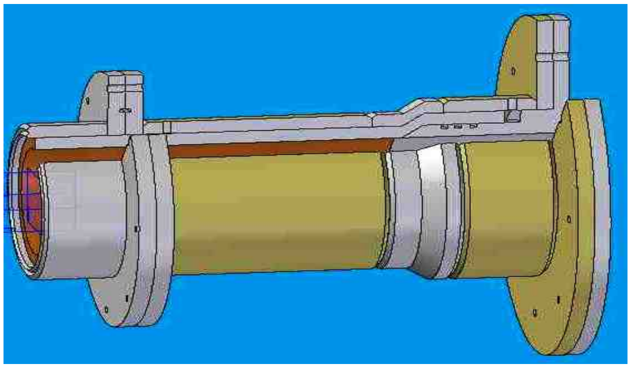


Figure 6. Conceptual View of the End Connector

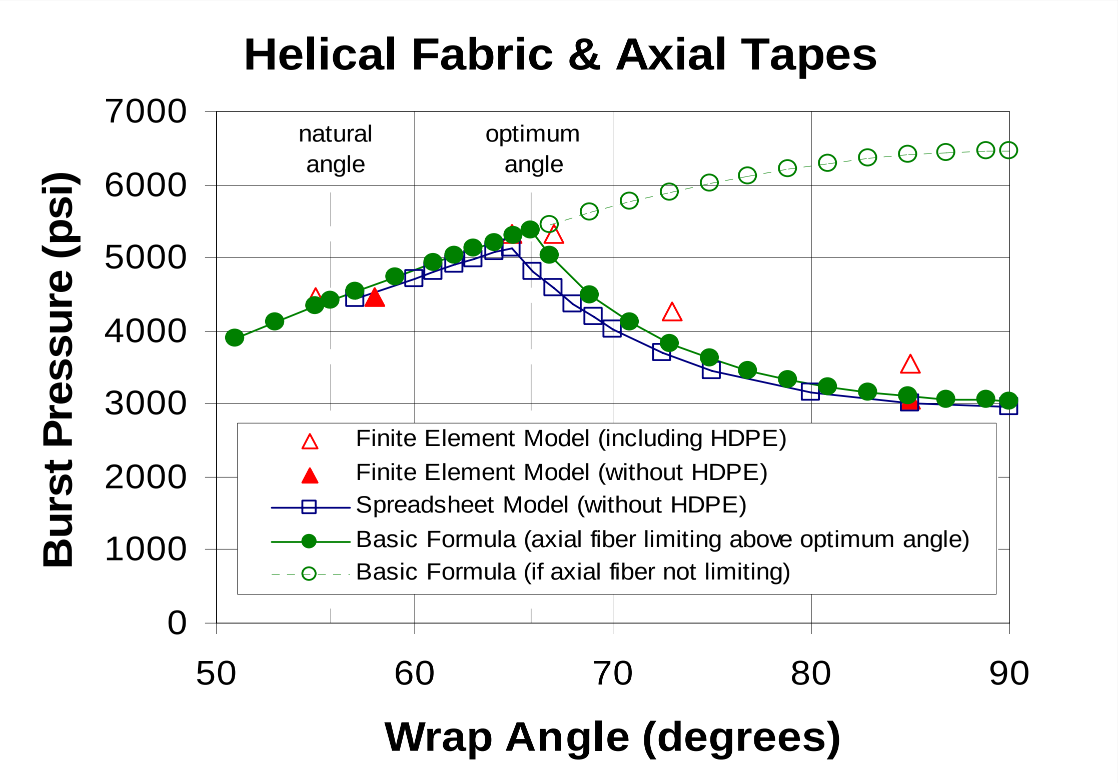


Figure 7. - Example Calculated Burst Pressures as a Function of the Helical Wrap Angle for a Nominal 10 inch Diameter Pipe Liner

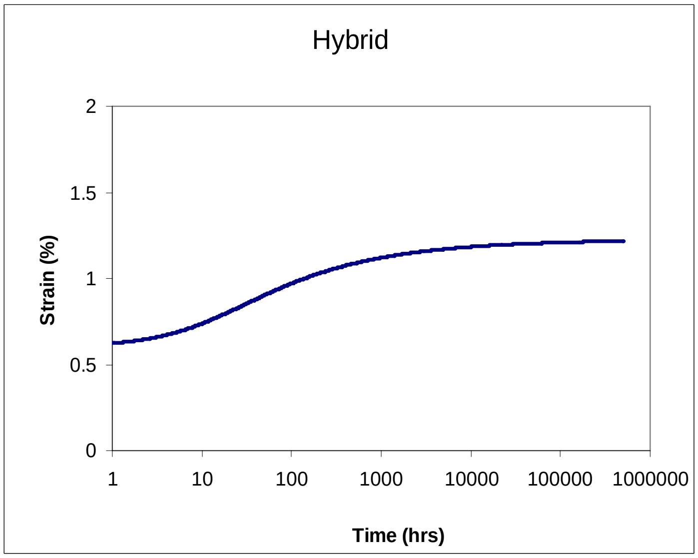


Figure 8. - Predicted Long Term Strain in a Hybrid of 70% High Performance Polyethylene Fibers with 30% Carbon Fibers under Constant Applied Load