COMPOSITE RISER

EXPERIENCE AND DESIGN GUIDANCE

prepared for MMS as a guideline for composite offshore engagements

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EXECUTIVE SUMMARY

Composite Riser Experience and Design Guidance presented in this report captures the latest state of the art advances and experience in the academia as well as in industry for the design and manufacturing of production risers with continuous fiber reinforced polymer matrix composites for deepwater top tension risers. The contents have been discussed and revised based on the feedback of a team of industrial composite experts.

Composite materials, especially glass-epoxy and carbon-epoxy composites, have drawn substantial attention from the offshore industry primarily due to their high specific strength as well as the tailorability of strength and stiffness, thermal conductivity, damping properties. Integrated experimental and computational approaches are mature and feasible for both prototype designs as well as for the material/structural characterization necessary to develop design allowables. On the other hand, the low-cost and reliable manufacturing techniques that can produce defect free components with simple and robust attachments need further development. At present, the principal barrier is the lack of databases commensurate with field trials that can be utilized with confidence for design life. Still the long term advantages of composites are worth the investment. Metrics for successful transition firmly reside in the development of field databases, robust terminations, standards, and flexibility in selecting optimum production/exploration platforms to take advantage of composites. The development of industry and regulatory acceptable design standards can greatly facilitate the approval process.

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1. Overview

1.1 Scope

This guidance is intended to inform the readers, MMS Staff Engineers, of the design and analysis considerations that are unique to offshore composite risers. The report presents the latest state of the art advances and experience in the academia as well as in industry. The contents have been discussed and revised according to the feedback of the industrial composite experts team with MMS participation in a thorough review panel. The scope of the present guidance is limited to production risers that are to be designed and manufactured as continuous fiber reinforced polymer matrix composites to be used as in deepwater top tension risers. The reader is encouraged to assess the possibilities and inherent innovations associated in utilizing composites with full appreciation of its present state-of-the art capabilities.

1.2 Introduction

Even though composites are relatively mature in design and manufacturing arenas within aerospace applications, composite structures for offshore face a qualification challenge and must bring recent advances and experiences to enable competitiveness. System level design and analysis must be adopted for an economic payoff by integrating material, mechanics and manufacturing aspects to predict life cycles. Since most of the offshore engineers are unfamiliar with composite design, it is necessary to demonstrate that a composite riser meets the same requirements as the traditional steel risers at the onset.

Composite materials, especially glass-epoxy and carbon-epoxy composites, have drawn substantial attention from the offshore industry primarily due to their high specific strength. The tailorability of specific strength and stiffness, thermal conductivity, resistance to corrosive fluids, increase in damping are properties unavailable in any other material system. Weight reduction that can be attained by using a composite production riser is substantial and will lead to significant cost savings especially when design is holistically executed at a full system level. In order to take advantage of the tailorability of the many constituents, the operating environment must be clearly defined. This is a very important aspect since physical requirements are essential to populate the design allowables. The principle obstacles in moving ahead with installation is rooted in the lack of design-material database, consistent with past experience and recent advances with nondestructive evaluation (NDE) techniques and perceived manufacturing costs. In the ultra-deep water applications, the tendency to replace steel with composite from the mere perspective of weight savings is a dangerous direction which may lead to short term financial savings yet will end up with actually a higher cost if the overall system concepts are not employed.

The idea of introducing composite materials for offshore applications emerged decades ago. At present, composites are utilized in various platform topside components, accumulator vessels, flowlines, spoolable piping and tubing, and flexible risers [1, 2]. As the interest in deepwater reserves grew exponentially, numerous attempts were made to develop composite tethers, buoyancy modules, and proto-type production and drilling risers to maximize the impact of the weight savings for deepwater operations. Although initially composites require higher manufacturing costs than steel, their impact on the overall system requirements and operational costs still make them an attractive option. The cost effectiveness of composites has been investigated in numerous studies [3-5] and the findings unanimously point out the decrease in payload translates to cost savings by decreasing platform size and mooring pretension. For example, for 700kips tensioner capacity range, a difference of one pound in the tensioner requirement is related to 2.11 times to the TLP size, while in the small top tension range, 500 kips or less, the ratio is only 1.33 [6].

The first attempt to design and analyze a composite production riser started in the 80’s by Institute Francais du Petrole (IFP) and Aerospatiale of France [4, 7, 8]. IFP/Aerospatiale riser was designed for a concrete TLP in 500-1000 m water depth. The riser body consisted of internal and external buna liners, helical wound carbon fiber layers (±20°), and hoop wound glass fiber layers (90°). The inner diameter and wall thickness were 9 in and 0.7 in, respectively, and the length of one riser joint was approximately 50 ft. The apparent weight of the riser including tubing and couplings was estimated as 30 lbs/ft and the mean top tension for 1000 m water depth was 165 kips. Tests on burst, axial tension, tensile fatigue, and creep were carried out. For the burst and tension tests, failure occurred at 15.9 ksi and 1,047 kips respectively. The tensile fatigue tests demonstrated that the riser has sufficient fatigue resistance, surviving after three times the number of cycles that would fail a steel riser.

In the mid 90's two joint industry projects sponsored by National Institute of Standards and Technology (NIST) Advanced Technology Program (ATP) focused on developing a composite production riser [9-14] and a composite drilling riser [15-17]. NIST/ATP production riser (with single as well as duals casings) targeted 3000 to 5000 ft water depth. The composite wall had more complex construction than the IFP/Aerospatiale design where carbon/glass hybrid hoop layers in addition to carbon helical layers and glass hoop layers were implemented leading to total weight of 27.0 lbs/ft including fittings. Numerous tests, including axial tension, burst, collapse, static fatigue, and impact tests, were performed on short length and full-scale samples. The burst, collapse, and axial tension capacities as reported exceeded the requirements, reaching 11 ksi, 3.5 ksi, and 825 kips. Impact tests with 1000 in-lb drops lead to 48% reduction in burst strength and 25-39 % in axial strength. In this effort, more than seventy composite tubes with MCI coupling were tested under static-load, static fatigue, and cyclic fatigue conditions to demonstrate design accuracy, fabrication repeatability, and performance.

In the latest joint industry project, Magnolia, several composite production risers were developed to demonstrate the feasibility of its design and fabrication to satisfy the same requirements as conventional steel risers on the Magnolia TLP in the Gulf of Mexico at 4,700 ft water depth. The ultimate goal of this effort was to replace a few steel joints with prototype composite joints to gain in-situ experience and data. Not all the details on the wall construction of the Magnolia composite production riser are in the open literature, however it is known that the initial design had two inner liners, steel and rubber, and later it was modified by adding a secondary steel liner between the rubber liner and structural composite layers. Regrettably, this demonstration project did not proceed to installation at the GOM due to welding protocol problems at the metal liner-termination interface prior to its installation.

1.3 Requirements

The main functional requirement of a production riser system is to convey fluids and gas from sea floor to a surface platform. Thus the overall requirement can be decomposed into two sub-requirements: fluid/pressure containment and structural integrity throughout its service life.

A production riser must assure fluid tightness. Composite materials in general are not expected to possess perfect fluid tightness, and usually additional liner(s) are used as barriers against the fluids. In addition, the riser should maintain sufficient burst capacity against high internal pressure resulting from tubing leakage and resist collapse by external pressure. Since the composite body has multiple layers in addition to liners, burst and collapse analyses require extra emphasis. It should be noted that a composite riser can lose its containment capability without suffering a major structural damage in the composite, and the design should minimize the loads directed to the liners.

To ensure the structural integrity of the riser, several design load cases are analyzed at the global scale which then can be translated to a local scale at a specific location(s) of critical interest. Unlike typical isotropic materials, the state of stress in a composite laminate cannot be obtained directly from a global analysis in a single step. The details and the rationale of global-local analysis based on instantaneous combined load effects will be presented in Section 5. Fatigue analysis should also be performed to investigate the cumulative damage from the long term service.

After confidence in a design is gained through a series of analyses, qualification testing must follow. Basic capacities such as burst, collapse, tension, and fatigue are measured by tests, and the effects of combinations of loads should be examined. The designer should make a reasonable decision on the size of the test specimen. In some cases, a short riser segment with full diameter instead of a full joint may be used. The continuous exposure to service conditions (aging) of the termination for systems with polymeric liners is as important as the aging of the tube body for long term 10-20 year life cycle predictions. Without a strong connection to the service and operating environment for a given application, a realistic accelerated aging study can not be conducted to address durability and reliability issues. For these studies, prototypes selected through careful similitude models, can be tested and closely monitored to obtain local and global strains and moduli information along with useful NDE measurements such as acoustic emission, optical fibers, and laser tomography. There must also be statistically robust number of repeatable tests.

2. Composite Riser Body and Terminations

A key feature to address at the termiatination site where the composite body is joined to the metallic connector is the state of residual stress. Specifically for composite joints with metallic liners, the residual stress distribution generated during fabrication must be accounted in deliberations about deciding design allowables.

2.1 Liners

Often internal and/or external liners are added to the structural composites to ensure fluid-tightness. The primary function of an internal liner is to prevent leakage from the annulus. The liner material is also required to resist corrosion and abrasion. Typical internal liner materials include synthetic rubbers, thermoplastic polymers, and structural metals (steel and titanium). There may be multi-layered liners where each layer is made of different materials, for example, steel and rubber. When a polymeric liner is used, bonding between the liner and structural composite laminate is critical, since debonded areas can be vulnerable to collapse due to pressure buildup at the interface and internal under pressure.

In general, an external liner may provide fluid and pressure tightness against sea water and protection against external impact and gouging. Again, synthetic rubbers and thermoplastic polymers are generally used to satisfy these requirements. Additional glass fiber wraps may be applied as sacrificial layers. The external liner material is required to resist environmental effects and corrosion resulting from direct contact with sea water, temperature, UV radiation etc.

2.2 Structural Composite Body

Structural composite is the major load bearing element. Generally, this part consists of alternating hoop and axial reinforcements. The mechanical properties of a riser in these major directions can be tailored to the requirements with some coupling effects. Since significant weight reduction is achieved through using composites, the composite riser with the high specific stiffness would experience much lower axial tension and bending moment than its equivalent steel riser. The percent of hoop vs. off-axis (nearly axial) layers would be based on operation conditions and loads.

The most common fibers are carbon and glass, whereas the epoxy resin is widely considered as a matrix of choice. Glass fibers have lower modulus and strength in comparison to carbon fiber. However, they are more economical and offer better shock resistance. Carbon fibers have excellent fatigue properties, chemical resistance, and high stiffness and strength. Sometimes both carbon and glass fibers are used to create hybrids, either in the plane or through the thickness. What is of critical importance is that both the selection of constituent materials and manufacturing process must ensure a strong interface, minimum defects, and excellent wetability when the resin is introduced. Further interface enhancements can be attained by proper sizing and coating of the fibers.

In axial layers, the fibers are generally as closely aligned with the global riser axis as possible. Due to manufacturing constraints typical helical winding angles are less than ±10°, In this case, the axial effective stiffness and strength will be slightly compromised. The thicknesses and orientations of these axial layers largely influence the riser response under combined axial tension and bending moment.

The orientation of hoop reinforcements is 90° or near 90° with respect to the global axis. The hoop layers are the deciding factor for the burst and collapse resistance of the riser, and therefore, they are sized to assure the required burst and collapse capacities. An interplay is always in action when the liners are metallics. Thus adjusting liner thickness vs. the number of hoop layers becomes an optimization parameter. If the hoop layers do not provide enough stiffness, a large thickness for the internal liner will be required to prevent premature failure of the liner impairing the weight savings.

2.3 Metal-Composite Interface Termination

Metal-Composite Interface (MCI) should provide a secure connection between the composite body and metal couplings at the terminations of a riser joint. The primary requirement for an MCI design is to effectively transfer loads from the connection to the composite tube. The most common design is the traplock joint where the MCI consists of a series of grooves (trap), each of which traps a group of composite layers secured by additional high modulus composite wraps. This concept has been proven through multiple applications, such as NIST-ATP and Heidrun, and complete requirements and additional details of the traplock concept can be found in references [18-20]. Under combined axial and pressure loads, the preferred failure is more likely to occur at this site rather than the tube body [13]. Therefore, it is recommended that the MCI design possess robustness as well as a thorough qualification of the fabrication techniques including welds at the metal-composite interface.

At times, one can argue that if the resin selection was based on long term testing of reinforced coupons that were manufactured the same way, the allowable strain and stress response for failure initiation must hold for the actual riser tube. This is very unlikely since the riser, due to the termination geometry and the taper in the thickness along the MCI interface, will not experience the same state of residual strength. The load path under mechanical loads will also be different. Therefore there needs to be a patient development of series of meaningful model test specimen geometry to capture the intricate details of the full size tube. One must understand and verify the contribution of the MCI termination section both to manufacturing and operational induced damage initiation and progression as a function of loading history. At present, the terminations offer the most potential for improvement and need experimental data the most. The length (thus volume and mass) of a metal connector is considerable and takes away from the weight savings in a conventional 40-70 feet long composite riser joint. The debate over metal-composite interfaces with mechanical locking (trap joints) and bonding requires full testing to the design load limits. In addition to sustaining the mechanical load, it must also survive the service environment. The thermal gradients imposed on the riser wall at a given depth due to the different seawater temperature and that of the fluid contained in the risers and their cyclic nature overtime must be considered in the analysis as well as the 5, 10 and 100 year storm conditions. This in general does not present any computational handicaps, until one must come to terms with the material properties that one must identify them as a function of time. Otherwise, the computational output can not be predictive in nature for risers with polymeric and elastomeric liners.

2.4 Manufacturing

The primary feature is the selection of a cure cycle that will minimize the processing defects. Parameters that are of critical importance to eliminate are residual stress induced microcracks. However, when approaches such as open mold and continuous filament winding for tubulars are introduced, the control of temperature, the tension on the reinforcement tows to keep them from sliding off the mandrel, UV additives, viscosity of the resin, post cure conditions-temperature, duration and the length, bring in conflicting requirements. The actual design of mandrel for easy take off of finite length as well as continuous tubulars also requires composite manufacturing expertise to minimize the CTE mismatch of the composite, mandrel and the MCI termination.

The impact of selected manufacturing approach on the constituent response of composites must be evaluated both at lamina and laminate scales. How the fiber tows are placed and if adequate resin wetting occurs entirely depend on the fabrication technologies (e.g.; braiding, pultrusion, filament winding) and the reinforcement architecture (tape, tow, textile). A simple unit cell describing the reinforcing fiber geometry within the resin can be used to study parametric concepts from volume fraction to potentially resin rich sites. Eventually these models can be extended to observe the initiation and sequence of damage mechanisms along with the residual stresses developed from thermal gradients during processing. Further refinements on such unit cell representations can lead to a successful incorporation of time dependent nonlinear behavior such as hygrothermal viscoelastic response.

In the presence of material nonlinearity, the damage mechanisms that lead to specific failure modes must be experimentally verified and can not be scaled up from laboratory test articles to field ready composite tubes. The matrix-fiber choices must be carefully based on the potential manufacturing conditions as well as the metal selection for the tailpiece at termination since residual stresses play a significant role during manufacturing of the tube on the mandrel with the tailpiece insert. Even if the metal-composite interface is designed and manufactured with great care, the next step where a flange maybe welded on brings forth additional obstacles. Primarily, the duration and the thermal gradients that this piece experiences during welding must be such that both the composite and the metal must be free from any additional strains and residual stresses.

The collective experience reported to date identifies some major common issues in wet filament winding of composite tubes as

- Inner liner (polymeric and/or metallic) placement; bonded vs. free
- Metal termination interface to be integrated to the mandrel

- Amount of a cure taking place during the actual winding
- Tension in the fiber tow to prevent misalignment-slipping on the mandrel
- Consistent tow impregnation and compaction of layers
- Defining post cure conditions-if required

Based on the different fabrication techniques, additional variables such as i.Tension on the fibers, ii. Viscosity control of the resin bath, iii. Fiber tow size 3K vs. 50K influences the quality of the composite. The thickness of the part is a significant contributor to the design of the cure cycle. The most promising technique as demonstrated in the NIST/ATP efforts is "wet" filament winding and partial curing on the mandrel with a follow up post cure cycle for tubular specimens. Nevertheless innovative concepts such as filament winding and subsequent braiding may offer solutions to overcome some of the hardships.

3. Materials

3.1 Constituent Material Selection

Most important is to match material selection to sustain long term service under environmental and mechanical loads. Minimum required properties to be evaluated are for matrix: E (Young's modulus), ν(Poissons ratio), CTE (coefficient of thermal expansion), CME (coefficient of moisture expansion), stress and strain at yield, strain at break, for fiber: E (Young's modulus), ν(Poissons ratio),, CTE (coefficient of thermal expansion), tensile strength, and tensile strain. It should be noted that these are customarily obtained in static, linear regimes for each constituent. However, one must realize that such (fiber and matrix characterized separately) independent properties only provide an overview of possible expectations and are not representative of nonlinear and co-cured behavior. That is there is a strong dependence on loading type, duration and conditions and especially the matrix response at the service temperatures need to be closely studied for the presence of any material nonlinearity, viscoelasticity and creep. Furthermore the neat matrix response versus fiber reinforced matrix response is not a synonymous behavior. Due to the heterogeneity and the anisotropy, the potential presence of processing defects and initiation and progression of damage modes will be significantly different. Thus after a simple identification of fiber and resin selection, the decision must be based on "composite" samples where proper attention is given to understanding the fiber tow -matrix interface.

The primary concern in resin selection is its resistance to moisture (water, gas or other fluids) ingress. Thus its vulnerability to matrix cracking in reinforced polymers during processing and/or under load must be thoroughly investigated and built into design allowables. The glass transition temperature (T_g) of a neat resin also serves as discerning criteria for its range of exposure during service and it is also critical in selecting the cure cycles. It has been widely discussed that in certain cases with moisture ingress, the T_g is reduced. However, this needs to be pursued within a well-defined and controlled environmental aging study that is tailored for each individual application. Further special treatments on the resin systems address series of additives, fillers to increase resistance to crack propagation, minimize residual stresses and shorten curing cycles.

Epoxy (most expensive and well-suited for filament winding) resin is best in strength and corrosion resistance, but moderately so in fire performance in comparison to phenolics. Phenolics offer great thermal and fire response, but they are vulnerable to moisture ingress. Vinyl ester is similar to epoxy with slightly lower strength and corrosion characteristics. Vinyl esters are successfully used for better chemical and environmental resistance in pultruded gratings for walkways, pipes and tanks. Polyesters (cheapest) have a long shelf life, and if unsaturated, offer controllable cures, i.e.; open mold processing. Isophthalics are most common in marine applications such as in the hulls of superstructures and mine hunters, but their fire performance is poor (toxic). Additives (alumina trihydrate) relieve this situation, but they change the viscosity making it harder to manufacture. Urethane methacrylate (modified acrylic) is preferred in pultrusion (used in cable ducting for the Channel tunnel).

	Advantages	Disadvantages
Epoxy	• well-suited for filament winding • very high strength • excellent corrosion resistance	• moderate fire performance
Phenolics	• great thermal and fire response	• vulnerable to moisture ingress
Polyesters	• long shelf life • controllable cures if unsaturated • low cost • Vinyl Ester: good chemical resistance	• Isophthalics: poor fire performance (toxic)
Urethane Methacrylate	• preferred in pultrusion	

Typical attributes of commercial resin types

3.2 Short Term Static Properties

Each layer of fiber reinforced composites as manufactured via filament winding is orthotropic, with three axes of symmetry. The material properties are described in terms of three principal directions: axial (1 direction), in-plane transverse (2 direction), and out-of-plane transverse (3 direction). Lamina properties are determined by the constituent material properties and the fiber volume fraction. The material properties are expressed in terms of characteristic values, where probability of exceedance and confidence level are taken into account. Since the resin is cured at an elevated temperature, a certain amount of residual stress always exists. The amount of tension applied to the fibers during the winding process is another factor, and it should be noted that the capacities of an actual riser joint may differ from those estimated from coupon testings.

3.3 Long Term Considerations

Properties of composite materials generally exhibit dependence on time, permanent static loads, and the environment. The selection of the conditioning temperature and duration is critical to create the accurate representation of service environment. The diffusion process is greatly influenced by temperature and thus may lead to unrealistic evaluation if it fails to simulate the operating conditions. The fluids that come in contact with the composite (inclusive of the liner) must be considered in their actual forms; i.e.; a "liquid" immersion or "gaseous" exposure. Unfortunately, there are not any fruitful generic conditions that can be used as a "catch-all" diagnostics. Typically chemical and environmental exposure studies need to include (as applications dictate) oil based and water based muds, seawater, NaCl, CaCl, HCl acid, scale inhibitors, and other corrosive fluids.

Choice of the resin should be based on high temperature performance and resistance to humidity and hydrocarbon as well as strength. Epoxy resin is the most attractive option in this regard, but its fire performance is moderate. Corrosion in composites is often interpreted as degradation of matrix properties and weakening (debonding) of fiber/matrix interface. Both of these occurrences lead to faster damage accumulation and poor fatigue life. On occasion, chemical phase changes can take place in response to aggressive gases or chemicals present in the transported fluids as well as exposure to elevated temperatures hastening microcracking and subsequent delamination. The galvanic coupling can be eliminated by designing in multiple layers of glass reinforcement to separate the metal from the carbon reinforcement layers. In addition to matrix and interface, glass fibers are known to be susceptible to sea water corrosion [4].

It is well known that the mechanical properties of epoxy resins are influenced by water absorption. Therefore, the properties in the directions transverse to the fibers are expected to deteriorate in the event of water ingress. Generally, the strength of the neat resin decreases significantly, while the modulus shows a relatively small decrease. Even though the strength of the fiber reinforced polymer matrix composite decreases due to water absorption as well, this change is not as severe as in the neat resin. It is reported that after a long term exposure (18 months) to pure and sea water, the tensile strength of carbon / epoxy composite rods decreased to 92.9 and 85.5% of the original strength [21]. On the other hand, another study indicates that there is no significant change in properties after a six month exposure to actual sea environment in various water depths [22]. Glass fibers exhibit fast loss of strength under sustained load near the static strength, while carbon fibers show much slower rate of loss.

In order to evaluate the degradation of the material constituents aged in seawater at temperature, carbon and glass reinforced epoxy laminates of different thickness and lay-up orientation have been examined analytically and experimentally [23-25]. The environmental scanning electron microscope images of unaged and aged laminates did not reveal any visible degradation associated with aging. In the computational models, the shear modulus and failure strains of in-plane hybrid lamina were obtained as a function of interface and nonlinear matrix properties, debonds, fiber volume fractions, and carbon to glass volume ratios and manufacturing residual stresses. Excellent correlation was observed between the analysis and test data for flexure response of laminates and burst pressure of tubes. Yet, these successful results can not be directly transferred to the large scale components.

Aging under sustained load and service environment is an area yet to be explored. The literature lacks in test data where combined loads are applied in actual sea environment. There are no standard test methods or specimen sizes established for aging studies. Also, accelerated aging techniques or procedures that can yield data equivalent to target durations of long term exposure need to be developed. Some of these shortcomings are rather simple to overcome by utilizing specimens with excellent genealogical records and utilizing actual fluids in the tests and applying combined loads. What is not straightforward is the mechanism of acceleration which must be done with a very thorough failure initiation and progression intent and taking multiple incremental increases.

Permanent static loads may cause creep and static fatigue (stress rupture). It is recommended that a set of long term strengths [5, 13], instead of static strengths, should be used as the allowables for the composite. A reliability-based approach for determining the ratio of the mean static strength to the mean of the load distribution under sustained loading is discussed in Ref [19].

3.4 Cyclic Fatigue Properties

Although there is no single composite fatigue design and analysis procedure that is generally agreed, the S-N curve approach is the most common method for life estimations for composites. An S-N equation is typically represented in the form of a log-log relationship. Some S-N data may better fit a second degree polynomial on a log-log scale or the semi-log form. Carbon fiber reinforced composites do not typically display an endurance limit. It should be noted that the S-N relationship must faithfully represent the data in higher number of cycles range. Some laminates show gradual loss of stiffness over the load cycles before failure, while other laminates may lose their stiffness in an abrupt manner. If stiffness reduction is clearly observed throughout the test duration, its effect on the laminate stresses should be adequately taken into account in the life estimation.

If the orientations of the axial and hoop layers coincide respectively with the beam direction and the actual hoop direction, i.e., a crossply laminate, shear becomes negligible and the hoop layers have little contribution to bearing axial tension and bending moment. In this special case, fatigue analysis can be carried out in the lamina level, where the hoop layers are assumed to be nonexistent, since matrix cracking in the hoop layers usually occurs first. When performing tests on a unidirectional lamina, the loading direction should coincide with the fiber direction, through which the tests replicate the loading on the axial layers. The fatigue data on a single S-N curve must represent a single R ratio, which is the ratio of the minimum stress to the maximum stress. If sufficient top tension is always provided by the tensioner, there will be no compressive stress, and fatigue data for a minimum of one or two R ratios between zero and one are required. In practice, many tests are conducted for an R = 0.1, and other load cycles with different R ratios are then extrapolated from the R = 0.1 tests. Obtaining fatigue data for multiple R ratios in general leads to better estimates.

Since carbon fibers have better fatigue resistance than glass fibers, hybridization by using glass and carbon fibers together can further improve overall fatigue response. Fatigue loading in general causes matrix cracking, delamination and then fiber tow failure by propagation. This is matrix dependent as well as reinforcement architecture dependent especially for initiation site and the subsequent propagation. Better fatigue performance is obtained from high modulus fibers and once again the binders and specialty fiber coatings play an important role for delivering a strong fiber matrix interface. High modulus carbon has the best mechanical fatigue performance to date followed by aramid and finally e-glass.

The fatigue analysis of the MCI (metal-composite-interface) for composite joints with metal liners is best undertaken through fracture mechanics. The possibility of crack initiation and growth at weld sites can be demonstrated analytically finite element techniques to address potential impact on fatigue capacity.

4. Design Philosophy

4.1 Selection of Geometry, Materials, and Load Conditions

The internal diameter of a production riser is decided based on the size of the internal tubing. Other factors include methanol injection, chemical injection, and control lines. Length of a riser joint varies from one system to another, typically ranging from 40 to 80 ft. It is recommended that the joint length should be extended to the point where the manufacturability permits, to avoid the complexity and weight gain induced by the terminations. Thicknesses of the individual components that comprise the wall should be decided interactively with analyses results. Appropriate thickness for internal liners should be decided based on the collapse resistance and burst resistance. Although metallic internal liner causes significant weight increase, it can contribute as a load bearing component and also can be used as a mandrel for composite winding. However, it is generally recommended that the contribution of liners as load bearing elements should be neglected in the analyses. In any case, failure of liners should always be analyzed. If a metallic liner is used, its impact on the system weight, cost, weldability, and fatigue life at welds should also be taken into account. Thicknesses of external liners should be decided based on impact and gouging considerations.

There is a great variety of composite materials, and they offer a wide range of properties. The property of a unidirectional lamina depends on the constituent (fiber and matrix) properties and fiber volume fraction. Laminate properties are decided by the orientations and thicknesses of the individual laminas. Therefore, desired effective stiffness and strength in the principal load directions are achieved by the choice of both material and lamination scheme. In general, composite wall structure should be designed to alleviate the stresses in the liners that are more susceptible to failure, rather than to sustain the load transferred to the composite itself.

A unidirectional composite lamina is orthotropic, and its stiffness can be defined by nine elastic constants, E_1, E_2, E_3, G_{12}, G_{13}, G_{23}, ν_{12}, ν_{13}, and ν_{23}. In case where the fibers are packed regularly in a hexagonal array, the lamina can be considered as transversely isotropic. For a transversely isotropic material, 2 and 3 directions are interchangeable, and the number of required elastic constants to characterize the material reduces to five: E_1, E_2, G_{12}, ν_{12}, and either G_{23} or ν_{23}. Furthermore, plane stress assumption is applicable to a thin lamina, and therefore, only four elastic constants, E_1, E_2, G_{12}, and ν_{12}, are necessary.

It would be highly uneconomical to perform global analysis of the entire riser system using 2-D or 3-D elements, and the mechanical properties of the laminate must be calculated using the lamina properties when modeling the system with beams. Under the plane stress assumption, effective in-plane moduli of a laminate can be obtained through the relationship between resultant forces / moments and strains / curvatures (classical lamination theory).

First, the reduced stress-strain relationship for individual layer in the global or laminate coordinate system is calculated through coordinate transformation. The resultant forces and moments per unit length of the laminate is simply the sum of the stresses of all layers, which can be expressed as follows when combined with the stress-strain relationship:

$$\{N\} = \int_{-h/2}^{h/2} [Q]^k \left(\{\varepsilon^0\} + z\{\kappa\}\right) dz$$

$$\{M\} = \int_{-h/2}^{h/2} [Q]^k \left(\{\varepsilon^0\} + z\{\kappa\}\right) z dz$$

where $\{N\}$ and $\{M\}$ are vectors of forces and moments per unit length and $\{\varepsilon^0\}$ and $\{\kappa\}$ are reference plane strain and curvature vectors. $[Q]^k$ is the 3×3 plane stress stiffness matrix of k-th layer in the global coordinate system, and h is the thickness of the laminate.

Using the fact that the strains are uniform for all layers, i.e., independent of through-thickness locations, the above load-deformation relations can be combined and rewritten with a 6×6 stiffness matrix, which consists of three sub-matrices, namely, extensional [A], extension / bending coupling [B], and bending [D] stiffnesses:

$$\begin{Bmatrix} \{N\} \\ \{M\} \end{Bmatrix} = \begin{bmatrix} [A] & [B] \\ [B] & [D] \end{bmatrix} \begin{Bmatrix} \{\varepsilon^0\} \\ \{\kappa\} \end{Bmatrix}$$

where $(A_{ij}, B_{ij}, D_{ij}) = \int_{-h/2}^{h/2} Q_{ij}{}^k (1, z, z^2) dz$

By inverting the stiffness matrix and considering uniaxial loading condition, the modulus for each global direction can be obtained.

Loads involved in riser analyses are usually classified into environmental, functional, and pressure loads. A riser system is subject to direct or indirect effects of environmental loads, such as wave, current, and wind. From the analysis point of view, input data related to environmental loads include statistical wave data for the specific location (usually in terms of significant wave height and peak period), current profiles, and platform motions. Functional loads are related to the system itself and its operation. Major functional loads include top tension, submerged weight of the riser, etc. Pressure loads embrace both internal and external (hydrostatic) pressures and are often considered as part of functional loads. Maximum internal pressure should be specified according to the application. Additionally, accidental loads should be defined by a risk analysis.

Design load cases are defined through creating realistic combinations of all types of loads mentioned above, to represent extreme combined load effects and limit states. The major conditions involved in defining load cases include storm, operation, and content pressure conditions and tensioner / mooring line failure. Also, an appropriate design case factor should be chosen for each design case. Load and Resistance Factor Design (LRFD) and Working Stress Design (WSD) are the most widely used design methods. LRFD involves multiple load effect factors and resistance factors, whereas WSD utilizes a single safety factor. In-depth discussions and details on the established practice related to loads, load cases, design methods, and load and resistance factors are available in numerous publications [26-29].

4.2 Definition of Damage and Failure Criteria

Since composites are non-homogeneous and composed of two or more constituent materials, there are multiple failure mechanisms: fiber breakage, fiber buckling, matrix cracking, fiber-matrix debonding, and delamination. One may occur as a result of another. In general, failure of a ply in the laminate is broadly classified into two failure modes: fiber mode and matrix mode. There are several largely accepted failure theories for composites, most of which are extension of well known theories for isotropic materials. Some of the theories consist of multiple sub-criteria and the failure mode is clearly distinguished, while other theories combine all the stress components and reduce themselves to a single criterion.

The simplest theories are maximum stress and maximum strain theories. These theories compare stresses or strains in the local (material) coordinate system with their corresponding allowables. Failure modes are conveniently and clearly identified by the individual criteria: fiber mode (tensile and compressive), matrix mode (tensile, compressive, and shear). However, interaction between multiple stress components is not taken into account. In Hashin's theory [30], the shear components are combined with the normal stress / strength terms, reducing the number of criteria to four. Other theories are in the form of a single equation, including Tsai-Hill which is an extension of von Mises criterion and Tsai-Wu which is a tensor polynomial [31].

Local failure in either mode causes stress redistribution in its vicinity due to loss of stiffness in the failure area. Stress redistribution may cause progressive failure if the stress or strain in the affected area exceeds the corresponding allowable as the result of the initial local failure.

Definition of failure is case dependent; in some cases, failure of one layer or layers of a certain orientation can be tolerated, but in other cases, they are considered as failure of the entire laminate. Matrix cracking, in general, does not severely impair the laminate strength provided that there are other layers whose fibers are intact and sustain the applied loads. Note that liners are incorporated to assure that leakage will not occur in the event such cracks are present.

4.3 Reliability, Risk, and Uncertainty Considerations

For metallic risers, failure can be simply defined as a through wall crack. Then a through wall crack is considered as the top event (failure) for a fault tree analysis, and it can be decomposed into sub-events, for example burst, fatigue, etc., according to possible failure scenarios, along with operational conditions that can lead to such events [32]. Risk is evaluated by calculating probability of occurrence for each sub-event incorporating uncertainties of the factors that define the event, such as applied loads and material properties.

This approach can be extended to composite risers only with refinement and restructuring, due to the multiple failure mechanism of composites and the fact that the fibers carry the most part of the loads. In addition to the non-homogeneity, the wall structure of a composite riser is more complicated than conventional risers, having internal and external liners made of different materials. Not only the load effects in the structural composite, but also the conditions of the liners should be taken into account when defining failure scenarios. For composite risers there can be multiple top events, since interconnected matrix cracks throughout the composite layers with breached liner may be considered as failure in some scenarios, while in other scenarios failure is not considered to have occurred until fiber breakage begins to take place.

5. Analysis Methods

5.1 General

Finite element method is one of the most useful design and analysis tools. Either widely accepted computer programs or specialized codes based on well-established principles should be used. If the designer has not undertaken a similar task, a benchmark study on a simplified problem with known solution is recommended. Type of element should be carefully chosen, and the mesh must be proven to be sufficiently fine for the given analysis. Such computational simulations are very useful in alleviating stress concentrations and designing fiber reinforcement architecture at MCI region to optimize it for best load transfer.

Rarely there exists a known closed-form solution for a composite structure. When using a closed-form solution, its applicability should be carefully examined in terms of the assumptions made in deriving the solution. A closed-from solution can serve as a benchmark for a finite element model which is simplified accordingly. It can be useful for verifying the integrity of the analysis input, as well as the appropriateness of the selected element.

5.2 Burst Analysis

Bust analysis can be performed with a relatively short riser FEA model where full or partial geometry with symmetry condition may be used. A liner may be regarded as layers in an element or must be modeled as separate elements, depending on the thickness of the liner, initial assembly stress due to autofretage and winding, and capability of the FE program. State of stress at the maximum internal pressure should be examined. Either discounted long term properties should be used or time dependence of the material properties should be incorporated. If applied pressure is increased beyond the maximum pressure to estimate the burst capacity, loss of stiffness should be adequately applied.

5.3 Collapse Analysis

Buckling / collapse discussed herein refers to hoop buckling / collapse. When the tensioner and applied top tension are designed to guarantee that there are not any compressive axial loads throughout the riser, axial buckling does not require particular attention. However, collapse due to the difference between external hydrostatic pressure and internal pressure should be analyzed, and the collapse resistance of the riser should be estimated. The required collapse resistance should be decided based upon water depth and internal under pressure. Since the rationale for introducing composite materials to offshore is to facilitate deep water production, composite risers are required to withstand high external pressure.

A rough estimate of the collapse capacity can be obtained through an eigenvalue buckling analysis. A cylindrical section model for this analysis should be sufficiently long, since critical pressure and mode shape are dependent on the model length up to a certain point.

Also, the buckling analysis requires finer mesh than other analyses, especially in the circumferential direction, enough to represent the mode shapes with multiple number of waves. In most cases, more detailed analysis, where the problem is solved as a continuous response instead of bifurcation, must follow the buckling analysis to check for any failure or effect of geometrical and material nonlinearity before reaching the critical buckling pressure. Internal metallic liner may yield while the structural composite is still intact and lose its capability as a load bearing component. The designer should select one of the known methods for stabilizing the structure or finding static equilibrium of the unstable problem. Also, appropriate geometrical imperfections, in the form of ovality or superimposed mode shapes, should be taken into consideration.

Collapse analysis of a composite riser is more complicated than that of a metallic riser, due to the internal liner. If the liner is not bonded to the composite, the liner may collapse by itself considerably before the composite body does, due to a pressure buildup by fluid penetration and accumulation. Even when the liner-composite interface is initially bonded, debonding may develop due to the fluids and mismatch of the material properties between the liner material and composite. When the bond between the liner and composite is not guaranteed, a case of completely debonded interface should be analyzed. The liner, when confined by the structural composite, may resist more pressure than it would if unconstrained.

5.4 Global Analysis

Global analysis of a composite riser system is performed in the same way as the well-established methods for steel risers, i.e. through representing them with beam elements. The effective composite modulus of the laminate as described in Chapter 4 is assigned to the beams. The analysis may be performed in either frequency or time domain. If nonlinearities are small, frequency domain analysis is more suitable. Otherwise, time domain analysis should be used. When performing time domain analysis with irregular waves, multiple replicates are required, and the duration of each run should be sufficiently long.

The loads listed in Section 4, environmental, functional, and pressure loads, should be incorporated in the analysis. Design load cases should be identified and the value of each load should be prescribed. Fluid induced loads to be applied are calculated by Morrison's equation with carefully determined coefficients. Top tension is decided based on the effective weight of the system. However, a composite riser may have lower stiffness than metallic risers, and in case there is concern over collision in an array of risers, consideration of a higher tension factor outside the typical range of 1.3-1.6 may be required. Platform motions, both low frequency and wave frequency motions and TLP setdown, are applied as forced boundary conditions, and relative motion between the riser and the platform should be allowed.

As discussed earlier, there are multiple damage mechanisms involved in the failure of composites where initiation and progression of such mechanisms and modes can be identified on the ply level, based on the local stress or strain components. Since the global analysis alone cannot provide sufficient information on the local state of stress required for the evaluation of failure, the global analysis is followed by local analysis.

5.5 Local Analysis

Based on the global analysis data, critical section(s) are selected where significant combined load effects are anticipated. Local model corresponds to the specific section with the identical length and actual cross-sectional geometry. Nodal forces and bending moment / displacements and rotation at the terminations of the critical section are applied as the boundary conditions to the local model.

The elements to be used for the local analysis should allow lamina properties and orientation of each ply as input and be able to calculate stresses of each layer. A fraction of the forces / displacements should be applied initially, and they are increased gradually until they reach the full value. At each load increment, the stresses or strains of each layer should be checked for failure using a failure theory. If a failure is detected, properties corresponding to the failure mode at the failure location should be reduced, so the local loss of stiffness results in stress redistribution to the neighboring layers and elements. This process involves not only the composite laminate but also the liners, especially those made of metals. If the local degradation of material properties are significant enough to affect the stiffness on the global level, global analysis may be repeated with the reduced stiffness at the particular location, and a new set of boundary conditions thus obtained are used.

Generally, fiber fracture does not immediately follow matrix cracking or liner failure. However, there is no definitive sequence of failure between matrix and liner; it depends on the materials and thickness of the liner. In case it is certain that the liner will be intact and matrix cracking is acceptable, the problem may be simplified to a situation where fiber failure is the only concern. Then it can be assumed that the matrix cracking is present throughout the model, and reduced properties are used in the entire analysis.

Local analysis is also performed to construct a failure envelope which serves as a failure criterion on the global level. In this case, the order of global and local analyses is reversed, and global analysis is performed after the local analysis has completed a failure envelope. A failure envelope consists of two main axes, axial load and pressure, and may include bending moment and torsion to form a four dimensional envelope. Numerous combinations of these loads are used for the local analysis to construct a complete failure envelope.

5.6 Fatigue Analysis

The previously discussed general global-local analysis procedure is for investigating maximum instantaneous stresses and possibility of failure. Although composite materials are known for their excellent fatigue properties, it is required that cyclic fatigue should be considered and cumulative damage and life should be estimated. The source for such considerations maybe rooted in either fluid-structure interaction such as VIV (Vortex Induced Vibration), or thermo-mechanical considerations that may be attributed to temperature gradients.

The first step of fatigue analysis is to collect sufficient sea states data. Generally, spectral fatigue analysis is performed, where a stress energy spectrum is obtained through a transfer function. Then the Rayleigh probability density function for each sea state is calculated, and finally probability for each stress magnitude becomes available. Alternatively, root mean square (RMS) stress at a location of interest for the given sea state may be used to calculate the Rayleigh probability density function.

Fatigue of composites is still actively being studied, and their behavior depends highly on constituent materials and lay-up. In general, matrix cracking in transverse layers, i.e., where the applied load is perpendicular to the fiber direction, takes place in relatively low cycles range and may be followed by delamination. Afterwards, axial layers alone carry the entire load. Reduction in the laminate stiffness caused by matrix cracking is typically as much as 10%.

There are a number of damage definitions proposed in the composites literature. Many of them have attempted to incorporate the effects of multi stress magnitudes and loading sequence using such concepts as residual strength and stiffness [33-38]. However, there is no single theory generally accepted and proven to be superior to Miner's rule. The major drawback of Miner's rule is that it does not incorporate continuous loss of strength that may occur in composites. Therefore, it is recommended that a resistance factor be adopted consistent with experience and operating conditions to account for the uncertainty [29, 39]. The residual strength concept does take this aspect into account, but it requires a definitive load sequence and more complicated calculations. This concept is yet to be extended to the random nature of loading that a riser experiences in its life.

For a cross-ply composite riser, fatigue analysis may be performed based on unidirectional S-N data. As a convenient and conservative approach, matrix cracking in the entire transverse layers is assumed to exist when calculating the stresses at the points of interest.

In this case, the analysis focuses on the outermost axial layer where the combined (tensile and bending) stress is most extensive. If a metallic internal liner is used, fatigue at the welds should be analyzed as well.

When calculating damage for a given stress magnitude, mean stress effect should be incorporated using a Goodman diagram or constant life diagram. When this process is not applied, it should be verified that using raw data yields more conservative results it is most meaningful to emphasize that experimental fatigue data range and the desired design life cycles are in sync both in amplitude and in cycles..

6. Inspection and Monitoring

Constitutive response characterization as well as life prediction and assessment of composites have high expectations from NDE applications, yet at present, the anisotropy, the heterogeneity and at times the inaccessibility of the components remain as challenges for the NDE community. Traditional NDE methods such as X-ray, acoustic emission and ultrasonic techniques do not have the resolution to identify the through the thickness location nor the type of damage in composites.

The presence of multiple constituents in the processing stage and subsequent manufacturing, transportation, storage and installation activities provide opportunities to assure that each phase has its own unique procedures. These are highlighted briefly as:

1. Inspection and testing of all raw materials (fibers, resins, adhesives, etc.)
2. Detailed specification of all manufacturing parameters (temperature, time, winding speed, winding tension)
3. Documentation of all specified process data
4. In-process inspection of manufacturing process and sample testing where appropriate
5. Dimensional and visual inspection

6. Ultrasonic and radiographic inspection, when feasible.
7. Proof load testing.
8. Follow-up by independent third party inspector.

Destructive testing of at least one joint should also be considered as an important element of the quality control plan. The destructive testing is used not only to confirm design and manufacturing, but also to develop monitoring parameters such as stiffness, local displacement and acoustic emission signature for use the quality of composite risers during proof load testing. Therefore, addressing it at the design, material purchase, manufacturing, and factory acceptance tests must ensure the structural integrity. Rigorous quality control procedures are applied in all steps of manufacturing of the composite riser. Following the manufacturing of the structural laminate and prior to installing the external liner and impact protector, it is recommended that the riser be inspected at a minimum at the MCI vicinity. After the completion of the manufacturing process, composite riser joints maybe subjected to factory acceptance pressure tests. It is also worthy to acknowledge that the composite components of the composite riser are designed to higher safety factors than those associated with the metal riser. While these steps exceed the requirements for equivalent metal systems, and they should ensure the long-term integrity of the composite risers, it is recognized that situations may arise that will require assessing the integrity of the joints after being in-service.

7. Conclusions

The development of industry and regulatory acceptable design standards can greatly facilitate the approval process. The user community is encouraged to develop a simple, robust in-service integrity monitoring system that does not complicate installation and operations that can globally monitor riser top tension magnitude and thereby sense weight changes that could result from riser flooding as an indicator of potential through-wall cracks. In the interest of optimizing the return on investment in the advanced composite structures for offshore applications, the critical decisions will rely on the strength and "satisfaction" with the engineering solutions for the triad of design, manufacturing, and inspection. The "know-how" associated with design is the most mature of these three. Integrated experimental and computational approaches are realistic and feasible for both prototype designs as well as for the material/structural characterization necessary to develop design allowables for each specific application. The fundamental analytical methodology will be based on the seamless interaction between appropriate constitutive behavior, structural response, optimization, and similitude models. The quality of low-cost manufacturing that will produce components defect free and introduce a reliable construction technology with simple and robust attachments need further development. At present, the principal drawback is the lack of databases commensurate with field trials that can be utilized with confidence for design life.

Still the long term advantages of composites are worth the investment. The tailorability of specific strength and stiffness, thermal conductivity, resistance to corrosive fluids, increase in damping are properties unavailable in any other material system. Metrics for successful transition firmly reside in the development of field databases, robust terminations, standards, and flexibility in selecting optimum production/exploration platforms to take advantage of composites.

- Identify service loads and life expectancy (load vs. time)
- Select manufacturing procedure that optimizes material system, terminations and strength(stiffness) selection(s)
- Develop multi-scale test matrix to evaluate hygrothermal and chemical aging under load as a function of time, temperature and stress state histories (nonlinear material and geometry)
- Describe potential damage mechanisms as observed in the above tests and incorporate them into constitutive models to track for progressive failure.
- Couple analysis and test results to converge on design allowables
- Field testing

The multi-scale test matrix development should not be mistaken for "perpetual specimen tests". This effort will introduce the development of appropriate specimens at different scales to enable realistic data gathering and to experiment with different inspection techniques.

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Glossary

Aging The effect or process of exposing materials to an environment for a period of time.

Braiding A process where two or more systems of yarns are intertwined in the bias direction form an integrated structure, in such a way that no two yarns are twisted around one another. A typical application is composite tubulars, and more complex shapes can be achieved by three dimensional braiding with controlled feed rates.

Coefficient of moisture expansion (CME) The fractional increase in length per unit mass variation due to the moisture absorption.

Coefficient of thermal expansion (CTE) The fractional increase in length (or in volume) of a material produced by a unit change in temperature.

Cross-ply A laminate which consists of plies oriented at right angles with respect to each other, usually at 0° and 90°.

Debonding A separation of a bonded joint or interface. A separation at the fiber-matrix interface in a narrow sense.

Delamination Separation of layers in a laminate along the plane of the layers.

Elastomer An amorphous, cross-linked polymeric material that reaches high elongations under tension and substantially recovers its original after being released.

Fiber reinforcement A strong fibrous material incorporated into the matrix to improve the properties. Filament is the smallest unit and usually of extreme length. Roving is a number of yarns, strands, tows, or ends collected into a parallel bundle with little or no twist. End is an untwisted strand of roving consisting of a given number of filaments gathered together.

Yarn is an assemblage of twisted filaments usually for weaving.

Filament winding A cost-effective process where fiber reinforcements (filament, tow, yarn, or tape) impregnated with resin are wound over a rotating mandrel. This technique can be used for building large structures.

Helical winding A winding process where the reinforcement fibers advance along a helical path with low angles from the mandrel axis.

Hoop winding Circumferential winding with an angle close to 90°.

Hybrid composite A composite with different reinforcement fibers such as glass and carbon fibers placed together. An interply hybrid is a composite laminate where different fibers are used in different layers, while an intraply hybrid has different types of fibers within the same unidirectional layer.

Hygrothermal aging Deterioration of properties due to moisture absorption and temperature change.

Lamina A single ply or layer in a laminate.

Laminate A composite structures (plate) where laminae or multiple layers are stacked and bonded together.

Matrix (resin) A homogeneous isotropic material in which fibers are imbedded. Includes metals and ceramics as well as polymers.

Metal-composite interface (MCI) An interface through which usually a filament wound composite tubing is joined to metal end terminations.

Microcracking Formation of microscopic cracks in the matrix due to high local thermal stresses.

Miner's rule A popular rule for estimating cumulative fatigue damages. The damage done by a single stress magnitude is defined as the ratio of contributing cycles to the cycles to failure, and the total damage is the linear sum of the damages done by individual stress magnitudes.

Open mold A family of low cost techniques for composite fabrication, including spray-up and hand lay-up, which utilizes single cavity molds and requires little or no external pressure.

Orthotropy A state of a material where there exist three mutually perpendicular planes of elastic symmetry.

Prepreg Resin impregnated fibers, in the form of roving, tape, or sheet. The resin is partially cured, ready for molding or winding.

Pultrusion A continuous process for manufacturing composites with uniform cross-sectional profiles. The fiber reinforcement, such as roving, passes through a resin impregnation bath and is pulled continuously into a shaping die to form the desired cross-section.

Thermoplastic matrix (resin) A plastic which is softened and flows when being subjected to heat and pressure and hardened upon cooling without undergoing cross-linking. On the other hand, a thermoset resin polymerizes into an infusible solid when cured by application of heat or chemical means.

Tow An untwisted bundle of continuous filaments. For example, a 3K tow consists of 3,000 fibers.

Unidirectional layer (ply) A lamina where all the fibers are oriented in the same direction.

Notation

E: Young's modulus

G: shear modulus

ν: Poisson's ratio

T_g: glass transition temperature

h: laminate thickness

R: load ratio, the ratio of the minimum to maximum stress in a cycle

$\{\varepsilon\}$: vector of strains

$\{\kappa\}$: vector of curvatures

$\{N\}$: vector of forces per unit length

$\{M\}$: vector of moments per unit length

$[A]$: extensional stiffness matrix within the laminate stiffness matrix

$[B]$: extension/bending coupling matrix within the laminate stiffness matrix

$[D]$: bending stiffness matrix within the laminate stiffness matrix

$[Q]$: lamina stiffness matrix for plane strain conditions

<u>subscripts</u>

1: direction of the fiber reinforcements

2: in-plane transverse to the fiber direction

3: thickness (stacking) direction

<u>superscripts</u>

0: reference plane

k: layer designation