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Composite Material Offshore Corrosion Solutions

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ABSTRACT

Corrosion and weight control are the two main factors motivating the interest and growth of the use of composite components in offshore oil and gas exploration and production operations. Controlling and inhibiting corrosion and periodic replacement of metal components costs the oil industry large amounts of money. Composite materials can usually be chosen which will resist corrosion and be compatible with the chemicals used downhole and offshore. Reducing the weight of deep and ultra deepwater floating platforms has become a high priority and low density composites yields the most effective solution. Oil and composite suppliers efforts, in part complemented by government support in the United States and Europe, have encouraged a slow but growing acceptance of the use of composites in offshore operations. Safety critical components such as fire water piping as well as secondary structure including gratings, handrails and stairs constructed of fiberglass and polymeric resin are now routinely specified for deepwater platforms. Significant advancements have been made in the materials (i.e., fire resistant phenolic resin) and in the design and fabrication methods used to address safety issues and to improve performance and reliability. More structurally demanding applications such as a high pressure riser tensioner accumulator vessels constructed of carbon and glass fibers have also been introduced offshore. Hybrid construction combining different materials to achieve the required structural performance while minimizing cost is another benefit derived from the design flexibility inherent with composites. This paper provides an overview of components currently used on offshore platforms and highlights proposed advanced applications under development.

INTRODUCTION

Properly designed, composite structures offer the potential to reduce maintenance costs, save weight, enhance safety, reduce adverse environmental impact, improve durability, and provide enabling capabilities. Some of the advantages offered by composite materials are listed below.

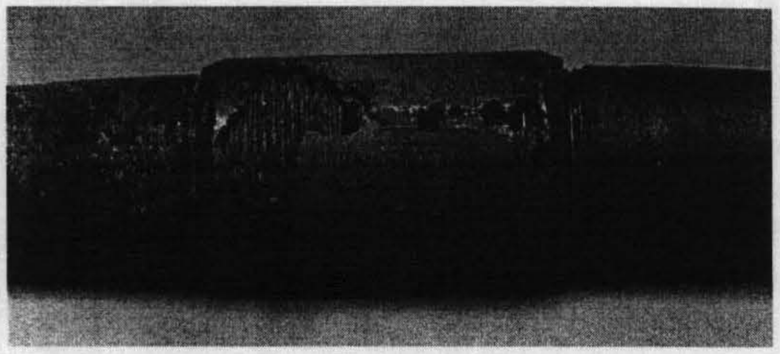
Some applications capture several of the advantages of composites making composites a clearly superior choice while other applications, for cost or special performance reasons, are better served using metals. The choice of materials has broadened and new developments will continue to offer even more options. Corrosion resistance and the associated cost savings provide good incentive for deployment of composites onshore as wells as offshore. Weight savings, however, are more valuable in deepwater offshore operations where light-weight components create synergistic benefits through downsizing of supporting structures and systems.[1-5] High strength or stiffness is the most important consideration for some applications while special properties such as electromagnetic transparency or low thermal conductivity may be important drivers for other applications. The use of composites also allows for greater design flexibility by allowing mechanical and physical properties to be tailored to meet specific design requirements and to provide improved cost-effective system solutions. On a one-on-one replacement basis, composite components can be less expensive than metals while other applications require life cycle costs be considered to capture cost savings. Advanced composite components constructed using higher cost carbon fiber are usually (but not always) more expensive than their steel counterpart. Weight and cost savings for the associated support structure and systems, however, can frequently shift the cost differential and make the integrated composite system solution less expensive. In addition, the economic incentive to use composite components can often be demonstrated based on their capability to improve performance and reduce life cycle costs.

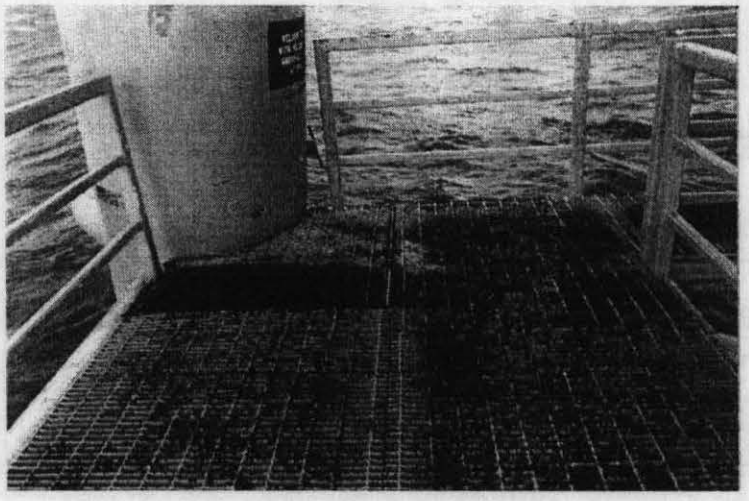
BENEFICIAL CHARACTERISTICS OF COMPOSITES

- Corrosion and Chemical Resistance
- Light Weight
- High Strength and Stiffness
- Fatigue Resistance
- Low Thermal Conductivity
- Low Electrical Conductivity
- Electromagnetic Transparency
- Easy to Install (Handle/Cut/Mill, etc.)
- Low Flow Friction and Wear
- Design Flexibility
- Integration of Electrical and Information Transmitters Into the Laminate Walls for Protection and Structural Monitoring

Over the last ten years composite have been accepted in the offshore oil industry for applications previously reserved for metals. Composite materials provide many desirable properties including those listed above, however, the two most common reasons to use composite materials in the oilfield are to avoid corrosion and to save weight. Illustrations of corrosion of steel pipe and gratings are shown in Figure 1.

(a) Steel pipe corrosion.





(b) Steel grating corrosion.

Figure 1.- Corrosion control is a major reason FRP is being used offshore.

Structural applications for a platform may be classified according to load range as heavily loaded (i.e., tendons, risers, and high-pressure piping), moderately loaded (i.e., helideck, flare tower, and low-pressure pipes and vessels), and secondary structure (i.e., gratings, ladders, ducts, and living quarters). The higher the load category, the less prepared is the state of the technology for near-term application. Another convenient way to categorize oil industry applications in the marine environment is by function or location as presented below.

COMPOSITE APPLICATION CATEGORIES

1. Platform to Sea Bed (tethers, riser, mooring rope, etc.).
2. Processing Facilities (containers, separators, pumps, etc.).
3. Topside Secondary Structure (grating, hand rail, etc.).
4. Housing & Protective Structures (accommodations, walls, etc.).
5. Topside Piping (Waste water, firewater, sea water, potable water, drains, etc.).
6. Tanks & Pressure Vessels (storage vessels, tanks, pressure accumulators, etc.).
7. Platform Structure (helideck, primary deck, hull, column, pontoons, etc.).
8. Downhole (coiled tubing, drill pipe, tools, sensors, etc.).
9. Subsea (umbilical, injection and flow lines, protection, etc.).
10. Ship Applications (pipe, containers, walls, mast, doors, pumps, etc.).

Deepwater oil and gas resources offer significant potential for development, particularly in the Gulf of Mexico, Brazil, West Coast of Africa and other deepwater basins around the world. Major oil companies, composite product manufacturers, oil service companies, and regulatory agencies have worked together over the last ten years in a low-key, but concentrated effort to advance composites technology and make composites a viable option for oil industry applications.[6] The technology has advanced and lightly-loaded secondary structures such as low-pressure fiberglass piping, gratings, and secondary structure are now routinely used offshore. Longer range, new composite applications are being developed to meet demanding structural performance requirements such as production and drilling risers, spoolable pipe, and high-pressure vessels. The highest payoff potential for composites is in deepwater associated with heavily-loaded, weight-sensitive applications where metal designs become impractical or extremely expense. Low-cost manufacturing processes and innovative hybrid designs which blind different materials such as glass and carbon are important factors in helping make composites affordable and competitive with metal designs. In support of these applications, qualification guidelines have been prepared to insure their quality and performance. Some applications in service, such as firewater ring main and deluge pipe, are extremely safety critical and demanding tests and guidelines have been specified to insure their safe performance. Recent depressed oil prices have delayed some offshore developments, but new discoveries are being made and when deepwater projects resume, composites are expected to play an increasingly important role in providing improved performance and helping make the cost of offshore development affordable. The present paper presents a review of existing and new composite technology being deployed and developed for the oil industry.

COMPOSITE MATERIALS BACKGROUND

Composite materials as used in this report consist of small diameter fibers of high strength and modulus embedded in a polymeric matrix. The fibers are the main load-carrying member while the matrix maintains the fibers in the desired orientation, acts to transfer load into the fibers and protects them from the surrounding environment. The most common fibers are glass, carbon and aramid supplied on spools such as shown in Figure 2. Other fibers such as silicon carbide, boron and aluminum oxide may have superior properties, but, are normally not used because of higher cost.

The polymeric matrix materials are classified as either thermoset or thermoplastic. The most common polymeric matrix materials are polyester, vinyl ester, phenolic, and epoxy. Fibers are incorporated in the matrix in long continuous lengths or are sometimes utilized as short discontinuous fibers. Structural composite components are normally formed by stacking several lamina (individual plies) to build up a composite structural laminate.

Fibers

A large number of fibers with different physical and chemical properties are commercially available. They can be obtained in several different physical forms including tow, ribbon, continuous woven mats and chopped strand mats. Fiber tow is the most common form used for high performance reinforcement. The fibers most likely to be used in the offshore industry are E and S glass, carbon and aramid. Table I provides an overview comparison of these fibers. Other fibers such as polyester and polyethylene are being used or considered in pure fiber form (without resin) for mooring ropes, but they are not expected to be competitive in composite form (with resin) due to their significantly lower modulus.

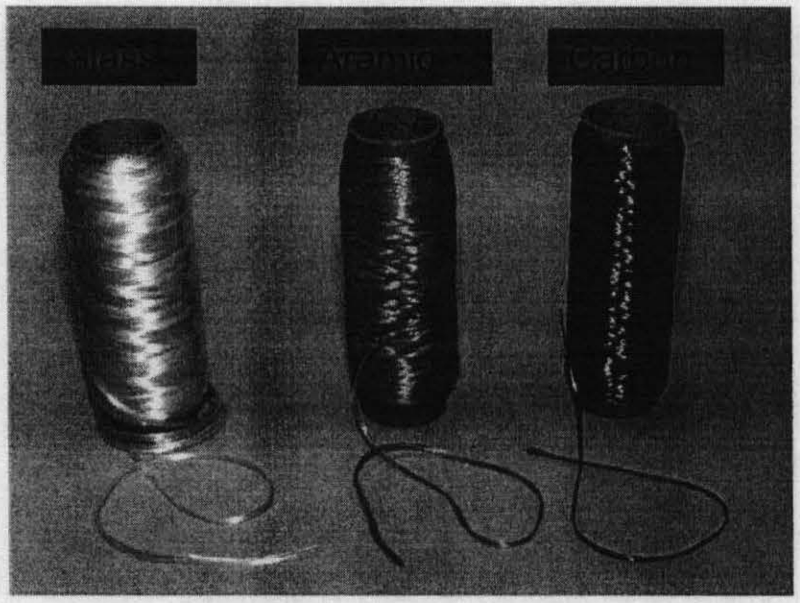


Figure 2.- Primary fibers used in construction of composites.

TABLE I.- QUALITATIVE COMPARISONS BETWEEN DIFFERENT CLASSES OF FIBERS.

Fiber	Advantages	Concerns
E-glass	Low cost	Moisture degradation
Carbon	High specific strength/stiffness Good fatigue and creep resistance	Higher cost Damage tolerance
Aramid	High specific tensile strength/stiffness Good damage tolerance	Low compressive properties High moisture absorption Difficult to machine

Resins

Resin selection requires consideration of properties (chemical resistance, toughness, abrasion resistance, stiffness, and strength), processing (lay-down rates, process temperature, and processability), and cost (materials and processing). Thermoset resins are more commonly used to make composites for oil industry applications than thermoplastic material. Epoxy, phenolic, vinyl ester, and polyester are the most commonly used thermoset resins. A wide variety of commercial thermoplastics are available. These include polyamide (PA - nylon), polyamide-imide (PAI), polyimide (PI), polyarylate (PAR), polyaryl sulfone (PAS), ployether sulfone

(PES), polyphenylene sulfide (PPS), high density polyethylene (HDPE), polyethylene terephthalate (PET), polyetheretherketone (PEEK) and polyetherketoneketone(PEKK). Thermoplastic resins are attractive because they offer good mechanical properties, exhibit excellent toughness and damage tolerance, display process repeatability, and simplify repair. Since thermoplastics have limited cross-link density, they typically exhibit lower chemical and creep resistance. Chemical resistance, however, can be improved by the development of crystalline morphology or by achieving active polymer linkages. Thermoplastic resins with an acceptable upper temperature range are usually more expensive than comparable temperature use thermoset resins.

Environmental Effects

In general, the fundamental mechanisms of corrosion are different for composites and metals. The lack of corrosion in the classical sense is one of the primary assets of composites. In most cases, metals are attached at the surface by electrochemical processes. Material degradation by diffusion of the material into the metal is not very common, with a few exceptions such as the process of hydrogen embrittlement of steel. Diffusion of material into a plastic material, however, is quite common and the effect ranges from negligible to catastrophic such as the dissolving of the plastic by certain solvents. The process may or may not involve a chemical reaction. For example, absorption of water does not usually involve a chemical reaction. To varying degrees for different polymers, water absorption can change the physical properties of the material such as lower the glass transition temperature, reduce the stiffness, and increase the sensitivity to creep. In addition, moisture and chemicals may attack the interface between the fiber and the resin. Carbon and glass fibers are relatively insensitive to the environment, except the strength of glass fibers can be reduced by water. A sizing coating applied during manufacture is used to protect glass fibers.

As with metals, not all polymers behave the same with regard to environmental exposure. In fact, the diversity of polymer properties allows the selection of a resin in most cases which will be compatible with most of the chemicals and environments experienced in the oil industry including alkalines, acids, caustic solutions, solvents, oxidizing agents, and moisture. Some resins also have superior resistance to high temperatures, tolerance to ultraviolet radiation and good performance in a fire. Phenolic resins, for example, perform well in a fire and emit low smoke or toxic decomposition components. Polyimide and some thermoplastic resins perform well at high temperatures, but are usually much more expensive than epoxy or vinyl ester.

Composite materials also exhibit certain limitations in performance. They are usually more susceptible to impact damage than metals and this must be factored into the design of components. Carbon fibers can also present a galvanic problem when they are joined to certain metals. Being at the cathodic end of the electromotive series, carbon fibers act as a noble metal being impervious to corrosion itself, but they accelerate corrosion in the adjacent less noble metal. Aluminum is more sensitivity to galvanic corrosion than steel and titanium is less sensitive than steel. Carbon fiber is compatible with some metals such as austenitic stainless steel, superalloys such as A286 and Inconel 718.[7] In making bolted joints, it is advisable to isolate the metal bolt from the composite using a sealant. Other precautions include coating cut and exposed surfaces. In bonded joints between metal and carbon, the primary protection against galvanic corrosion is the adhesive. Composite materials with glass or aramid fiber reinforcement do not present a galvanic corrosion issue.

Manufacturing

Assuming the application selected has merit, affordable composite structures depend on using a low-cost manufacturing process. In general, this implies that the manufacturing process be automated (not hand layup) and that glass fibers will be used if their properties are adequate. Hybrid construction incorporating combinations of glass and carbon or other fibers allows greater flexibility in reducing weight and meeting structural requirements while also paying close attention to the cost of raw materials. In aerospace, most composite components are made using prepreg tape in which the resin is put onto fiber bundles in a separate process. This improves the quality control, but adds significant cost to manufacturing. Preferred processes to reduce cost involve combining the resin and fiber at the point of application such as filament winding or placing the fiber into the part in a dry form and drawing the resin into the fiber.

Low cost manufacturing processes include filament winding, pultrusion, vacuum resin transfer molding (VRTM), and resin transfer molding (RTM). Sometimes it is necessary to use preform material such as stitched or braided material, but in general, the lowest cost process involves applying resin to fiber applied in roving form during the manufacturing process. If the application involves exposure to elevated temperature, the resin must be cured at a temperature higher than the application temperature. Most tubulars are constructed using filament winding while non-symmetric shapes can be pultruded. The critical parameters for making quality components are fiber wet-out, precision fiber orientation, and resin flow/consolidation and solidification.

CURRENT OFFSHORE COMPOSITE APPLICATIONS

Fiberglass Reinforced Plastic (FRP) Offshore Applications

Filament wound fiberglass pipe was first introduced into the oil field in the late 1950's. The lighter weight, fatigue and corrosion resistance and associated low life cycle costs make FRP components very attractive for expanded offshore applications. FRP components are from one-third to one-fifth as heavy as equivalent steel components and the lighter weight permits FRP products to be more easily handled and installed. FRP connections eliminate the hazards associated with welding and the experience level required to make quality bonded connections can be learned very quickly. The net result is that FRP composites can provide significant cost savings relative to metal.

There has been significant use offshore of FRP in the last five years in the Gulf of Mexico, Middle East, Far East, Africa and the North Sea. FRP pipe, however, has been used offshore for over twenty-five years. An example is the low pressure pipe used in Dubai in the water injection system with pipe ranging in size up to 36-inch in diameter as shown in Figure 3. In addition, FRP firewater pipe was used to replace steel pipe on all of the platforms in the Dubai Southwest Fatah field. In recent years, significant quantities of FRP have begun to be introduced into operations in the Norwegian sector of the North Sea including applications on Valhal,[8] Ekofisk, Ula, Statfjord, Gullfaks, Draugen, Troll and Heidrun. Environmental concerns also encourage the use of composites. An emerging design philosophy is to use non-corrosive composites to permit elimination of chemicals such as corrosion inhibitors required to protect steel pipe.

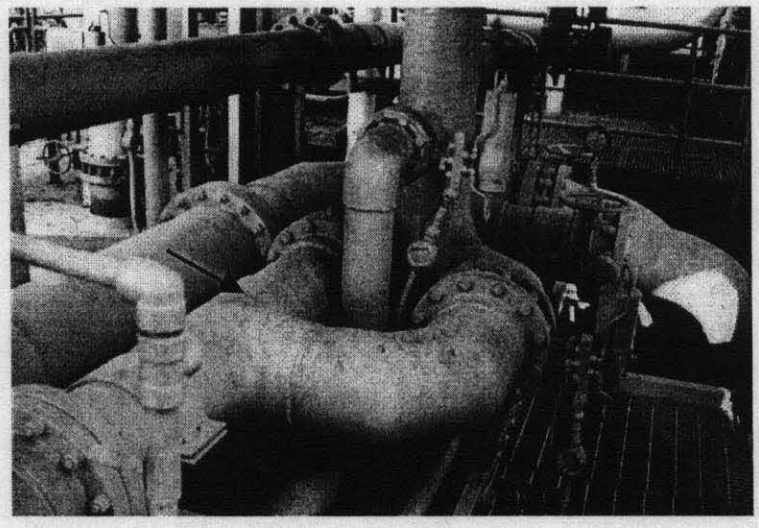


Figure 3.- FRP pipe installed on offshore platform in Dubai.

The total installed cost of fiberglass piping systems is on the same order as carbon steel and less than high performance alloys and copper nickel as shown in the Table II comparison of relative installed cost. The cost advantage for fiberglass pipe is most significant for large-diameter pipe and for complex installations since the higher cost for fiberglass pipe is offset by the lower labor costs of installation. Fiberglass tees and elbows can be installed in approximately 40% of the time required for the corresponding steel fittings. Fiberglass pipe carries a material cost premium of about 30% in 2-inch diameter, is approximately equivalent in price for 3- and 4-inch sizes, and is less expensive than Schedule 40 galvanized steel in the larger diameters decreasing to about one-half the cost for 12-inch pipe. In contrast, fiberglass fittings are generally 2 to 3 times more expensive in the smaller diameters, but cost about the same or less in the larger sizes.

TABLE II. - NORWAY, OFFSHORE INSTALLED PIPE COST COMPARISON.

Material	Relative Cost
Carbon Steel	**1.0**
FRP	**1.0**
316 Stainless Steel	**2.2**
CuNi	**3.5**

Much of the success in getting approval for FRP applications on platforms has been the result of focused R&D programs designed to advance the technology and to address specific issues of concern to the operators and regulatory authorities. Interaction of industry task groups with the NPD in Norway,[9] HSE in the U.K.,[10] and the MMS and Coast Guard in the United States is leading to the development of specifications and guidelines. Availability of industry accepted guidelines has been identified as one of the factors which will help make composite materials a viable option and permit selection based on performance and economics rather than prescriptive rules which favor metals.

Topside Applications of FRP in Gulf of Mexico (GOM)

Recent vintage deepwater Gulf of Mexico (GOM) platforms have made liberal use of FRP pipe to transport low pressure water and FRP grating.[11] In addition, secondary structural elements such as hand rails, framing, low-pressure tanks, etc. are also being used. This section provides representative examples of offshore composite applications.

A dockside view of the Marlin platform during construction is shown if Figure 4. The pipe suspended from the bottom of the platform with a U-shaped bend at the lower left is the firewater ring main constructed of glass fiber and polysiloxane-phenolix resin. The FRP deluge firewater pipe on the Marlin TLP shown in Figure 5 is qualified to resist a jet fire. A photograph showing FRP pipe used for seawater transport on the Ram Powell platform is shown in Figure 6. The use of FRP pipe for the firewater and seawater handling on the Mars TLP platform provided weight savings of approximately 80 tons. The FRP firewater ring main and deluge pipe used on recent GOM TLPs meet United States Coast Guard criteria defined in Policy File Memorandum PFM 1-98 16714.

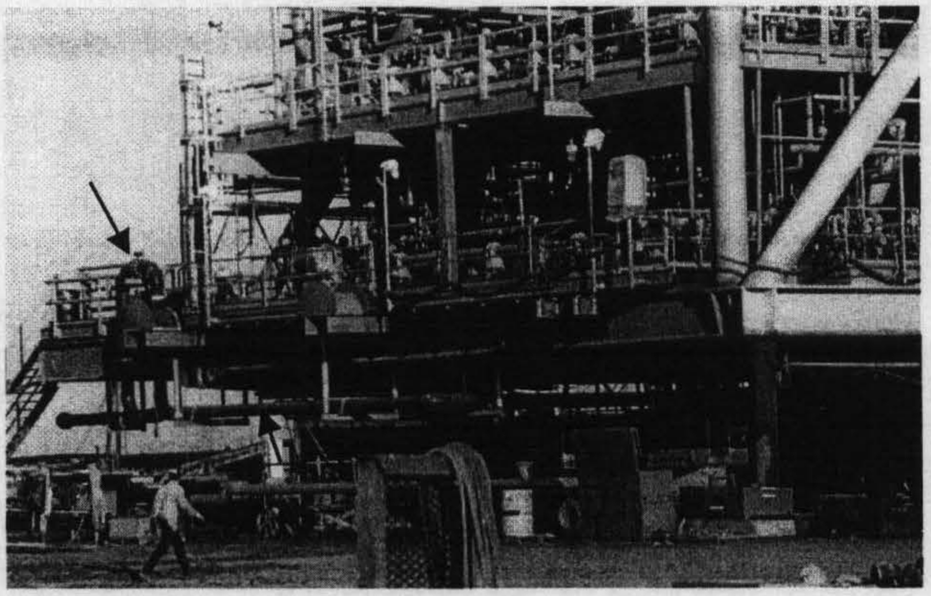


Figure 4.- FRP firewater ring main used on GOM platform. (Ameron)

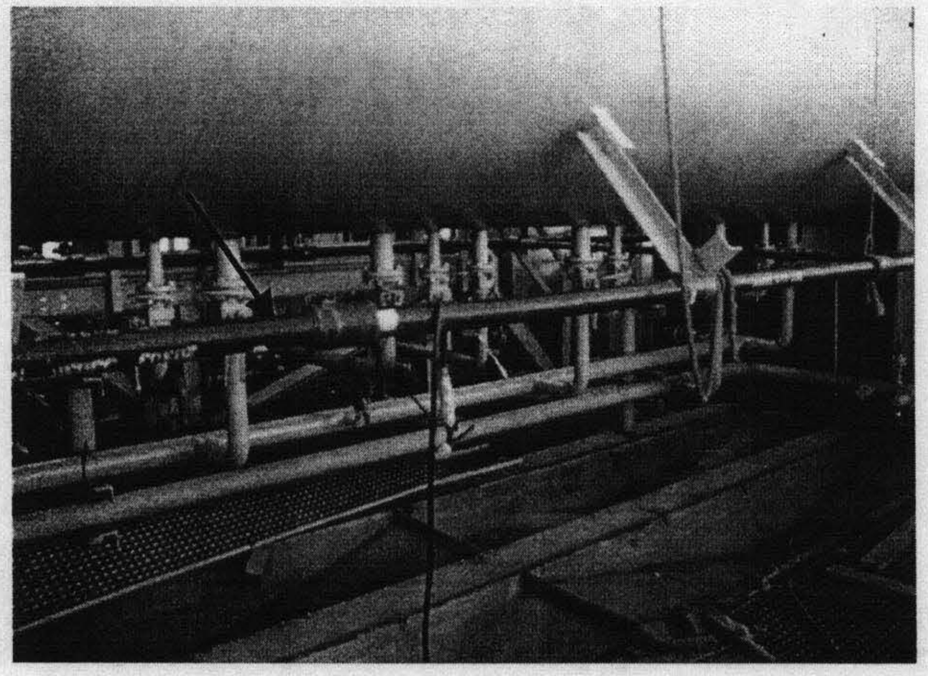


Figure 5.- FRP firewater deluge pipe. (Ameron)

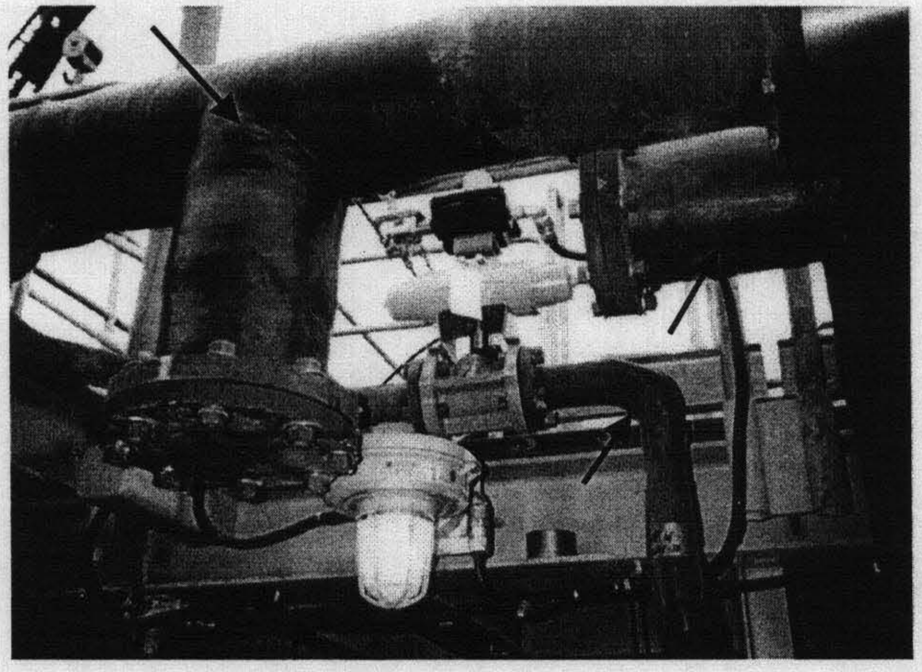


Figure 6.- FRP pipe used for transporting seawater on GOM platform. (Specialty Plastics)

The FRP grating shown in Figure 7 is constructed of pultruded glass fiber and phenolic resin to provide a more fire resistant product. Over 500,000 square feet of phenolic grating has been used on recent TLP platforms installed in the Gulf of Mexico. Weight savings of approximately 66 percent are provided by the FRP gratings compared to steel while the installed cost is approximately equal. Long term savings can be expected based on life cycle costs and reduced maintenance. Other benefits of the FRP grating is that shut-down due to hot work is not required during modifications and light-weight characteristics make handling easier. FRP gratings are also easier to walk and kneel on and have excellent anti-skid characteristics. The Strongwell FRP phenolic gratings pass rigid fire safety tests as defined in United States Coast Guard Policy File Memorandum PFM 2-98 9078.

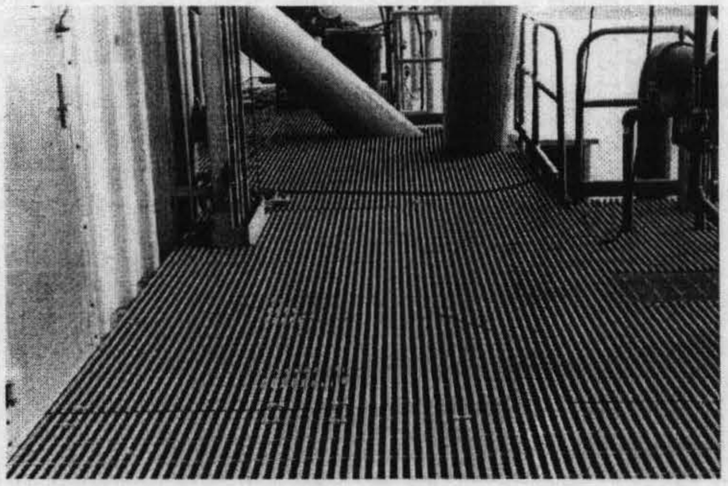
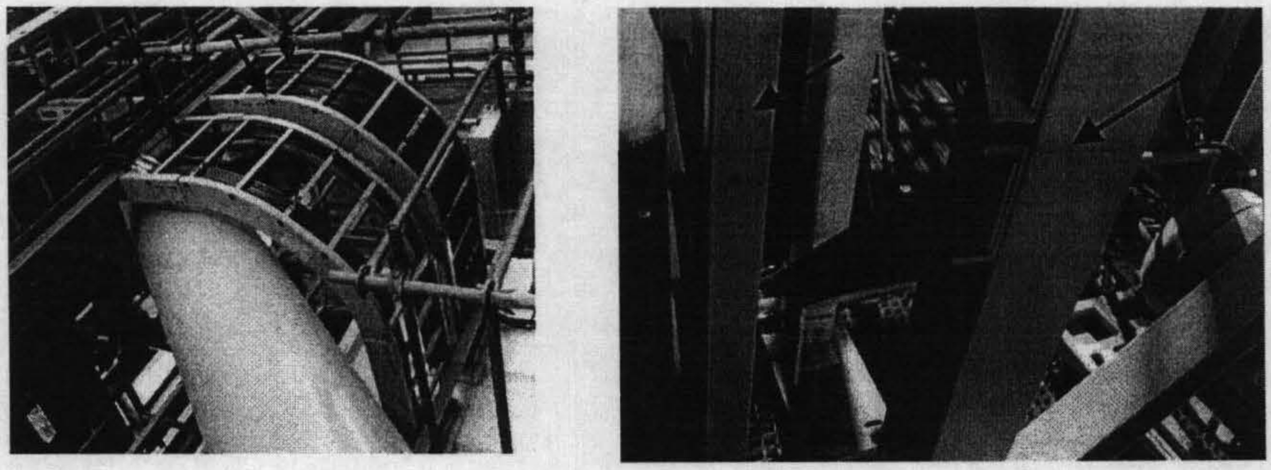


Figure 7.- FRP grating on GOM platform fabricated using fire resistant phenolic. (Strongwell)

A photograph showing FRP cable trays and secondary structure installed on Gulf of Mexico platforms is presented in Figure 8.



(a) FRP Cable Tray

(b) FRP secondary structure

Figure 8.- FRP cable tray and secondary frame structure used on GOM platform.

Composites on Small Unmanned Platforms

Many offshore oil and gas discoveries are small reservoirs in which the production rate does not justify the construction of a large supporting platform. To develop these reservoirs, small unmanned platforms are increasingly being used. Minimum facilities and accommodations are available and emphasis is placed on reducing the requirement for maintenance. An example is the Amoco Davy and Bessemer single leg mono-tower platform concept shown in Figure 9 which made liberal use of composites[12]. The platform is not normally manned and is designed for removal, refurbishment and re-installation at new locations making it sensitive to topside weight. Amoco identified the Davy and Bessemer topsides facilities as good applications for FRP materials because of the combined benefits of weight savings and corrosion resistance. The extensive range of composite material applications resulted in more than 100 tonnes weight saving for the 400 tonne topside. The FRP applications installed on Davy and Bessemer include: office, equipment room, tool room, handrails, ladders on topsides and on columns, gratings, fuel loading arm, drain pipe, caissons, diesel tank, lube tank and water utility tanks. Gratings and modules were made using phenolic resin to provide the required fire resistance. The handrails were manufactured using class 1 polyester resin. All other application were made using polyester resin except the caisson and drain pipe which used epoxy resin. The use of FRP for major structural beams and the helideck were attractive in terms of potential weight savings, but the time scale for design was too short for this to be an available option. Amoco studies indicate that there was no significant cost or weight advantage to using composite cable tray versus stainless steel trays.

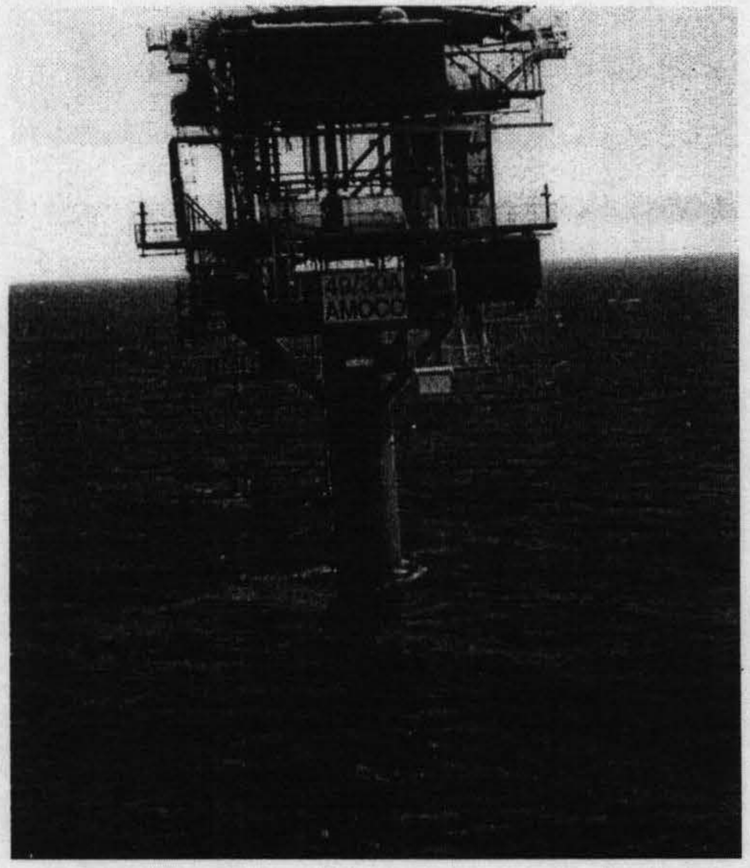


Figure 9.- Davy/Bessemer class of mono-tower platform designed for minimum maintenance.

POTENTIAL NEW OFFSHORE COMPOSITE APPLICATIONS

As the oil industry moves to explore and development ultra-deepwater reservoirs, weight and performance of critical systems become increasingly important. Some of the platform configurations used offshore are illustrated on Figure 10. The Tension Leg Platform has been the most widely used configuration for the 2000-ft to 4000-ft water depth, but recent studies seem to prefer the SPAR, particularly for water depths greater than around 3000-ft. TLP steel tendons become increasingly heavy at ultra deepwater depths due to the requirement to resist collapse of air filled tubulars. The applications with the highest return are those which provide a significant operational improvement such as extending the water depth of economical operation for a TLP or where reducing the weight of the component allows complementary weight saving in components and structures that support it. The riser is a good example of the latter because saving weight on the riser also saves weight on the deck structure and on the hull or buoyancy modules used to support it. For a TLP, saving weight on the riser also reduces the amount of pretension required on the tendons. Table III from reference 2 estimates the relative magnitude of the effect of selected components on other element of a TLP. In each case, the structural element being studied is given a relative value of 1. It can be seen for a TLP that saving weight on the topside payload and riser have the largest effect and saving weight on the hull has the lowest.

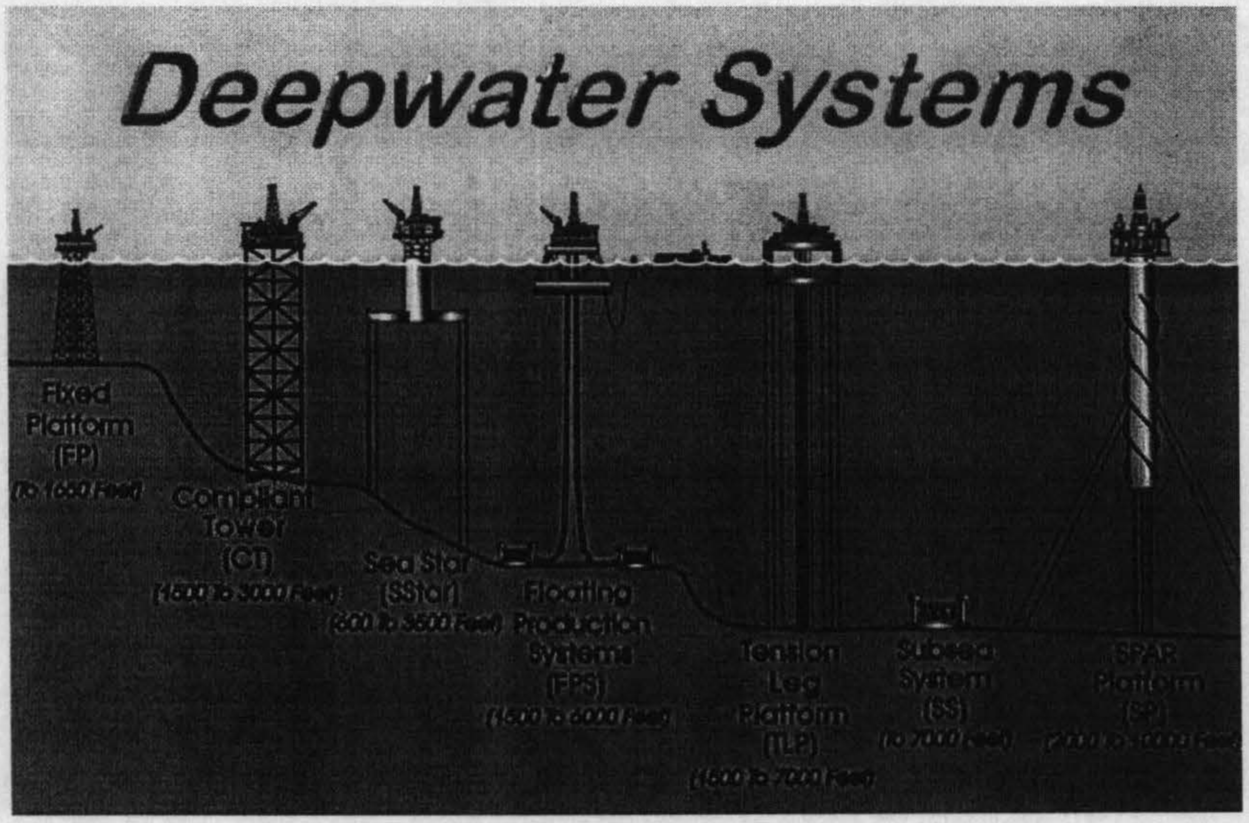


Figure 10.- Deepwater production platform configurations.

Table III.- TLP WEIGHT SAVINGS LEVERAGE.

Component	Hull (ton)	Deck (ton)	Payload (ton)	Riser (ton)	Tether Pretension (ton)	Total Savings (ton)
Hull	1.0	0	0	0	0.32	1.32
Deck	0.47	1.0	0	0	0.47	1.94
Payload	0.72	0.5	1.0	0	0.71	2.93
Riser	0.69	0.5	0	1.0	0.66	2.85

The remainder of this section highlights composite components currently being considered for deepwater platforms including the following applications.

- Production Risers
- Drilling Risers and Choke and Kill Lines
- Drill Pipe and Torque Tube Applications
- Buoyancy Modules
- Spoolable Pipe
- Platform Primary Structure
- Process Equipment / Pressure Vessels
- Accommodation Modules
- Tendon
- Synthetic Fiber Mooring Rope

Production Riser

A program to develop a composite riser was first initiated by Institut Francais du Petrole and Aerospatiale in 1985.[13-15] The program resulted in a successful prototype, but it was early in the deepwater development activity and the estimated cost was considered too expensive for the market. The drop in the cost of advanced composites and the accelerated pace of deepwater development in recent years renewed interest in a composite production riser. A joint industry project led by Lincoln Composites, in part supported by the National Institute of Standards and Technology (NIST) Advanced Technology Program (ATP), continued the composite riser development.[16] The 10.75-inch composite production riser is a hybrid construction composed of carbon and glass fibers embedded in an epoxy matrix. The composite body transfers load into a metal end coupling using a "trapped lock" design commonly used in the aerospace industry. The composite material is wound over and into a sculptured hill and valley profile in the metal which structurally links the composite body and metal coupling. Internal and external liners are incorporated to provide a fluid-tight barrier and protection from damage. The current design is suitable for water depths up to 5000 feet, but Lincoln Composites projects that a product can be designed to accommodate ultra deepwater requirements.

The NIST ATP production riser program involved an extensive test program with over sixty, 12 feet long specimens tested under different load conditions simulating the environment experienced in service including internal and external pressure and axial tension and fatigue. The average burst pressure for 6 specimens was 11,635 psi and the average axial load at failure for 6 specimen was 942 kip.[17]

A photograph showing a 50-ft long section of production riser is shown in Figure 11. The weight of the riser in air is 1450 pounds which represents a 41 percent weight savings compared to steel. The corresponding weight savings in water is 68 percent. This weight savings provides a significant impact on the platform design considering the long length from the platform to the sea bed and the large number of risers deployed a typical deepwater platform.

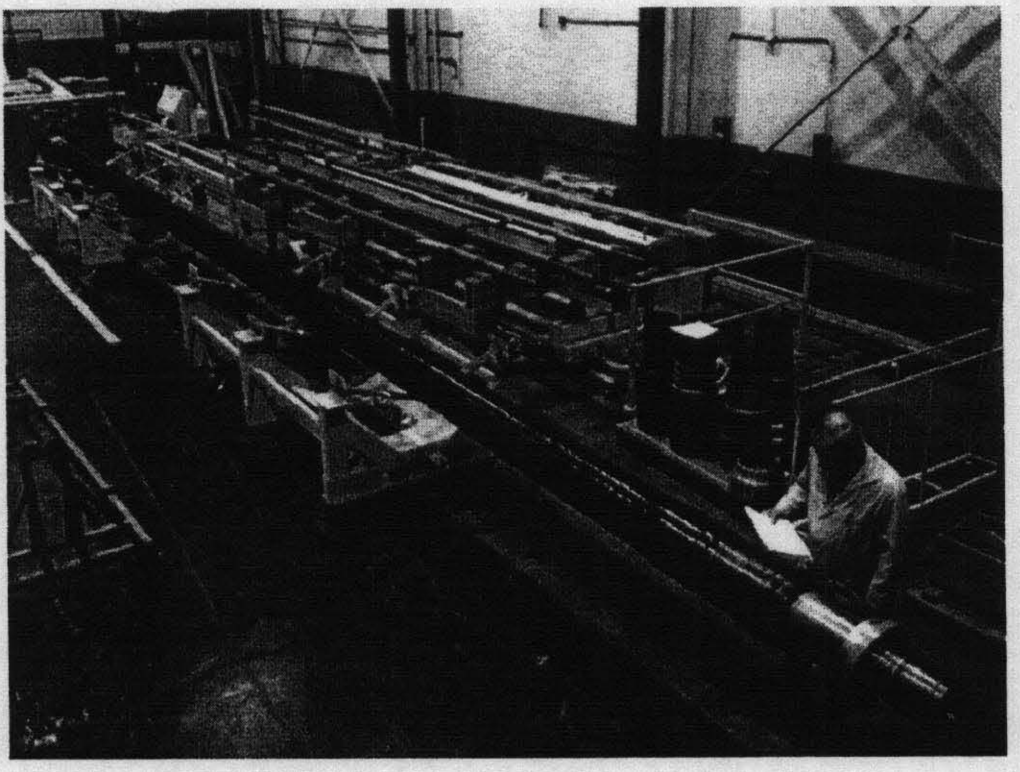


Figure 11.- Composite production riser. (Lincoln Composites)

Drilling Risers and Choke and Kill Lines

Two efforts are currently actively engaged in developing a composite drilling riser. One effort led by Northrop Grumman Marine Systems and ABB Vetco Gray is co-sponsored by NIST ATP.[18] The design requirements include 3000 psi operating pressure and 1.5 million pounds axial load. The drilling riser is constructed of carbon fiber and epoxy. Metal end fittings with a sculptured upset are over wound during the process of making the tube composite body and welded to a metal threaded end coupling. A 22-inch diameter prototype fabricated in this program is shown in Figure 12. Over 50% weight savings are projected for the composite drilling riser. The sponsors indicate plans to test the prototype in deepwater operations in Brazil. Northrop Gurmman Marine Systems and ABB Vetco Gray are also developing a composite choke and kill line.