FIBER REINFORCED THERMOPLASTIC SUCKER RODS FOR IMPROVING ROD PUMPING

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INTRODUCTION

Sucker rods are an essential system component for artificial lift rod pumping or rod lifting of oil and gas wells, but they have been limited using metals and thermoset based non-metal composites (i.e., existing fiberglass sucker rods).

Steel (metal) sucker rods have been limited, relatively, by a low corrosion resistance, a low strength to weight ratio (i.e., too heavy), a low fatigue endurance limit, and a low environmental, social and governance (ESG) rating during its lifecycle[i].

Composite thermoset glass fiber (fiberglass) sucker rods with a brittle resin matrix around the fibers have offered a high strength to weight ratio and greater corrosion resistance properties but have been limited by a relatively low tensile modulus of elasticity (i.e., too stretchy relative to steel), a high cost (i.e., higher cost relative to steel), and a low mechanical toughness (i.e., low tolerance to compressional loads, high impact forces/loads and torsional shear forces). Metal end fittings have also been a costly challenge for thermoset composite rods. Composite thermoset sucker rods using carbon fibers have proposed a tensile modulus of elasticity comparable to steel but have been limited primarily by a very high relative cost to steel sucker rods and a relatively low mechanical toughness. Thermoset composites have shown to possess an operationally risky failure mode, as the material fails in a brittle manner with extensive fiber splintering commonly referred to as "broom sticking".

Rod lifting has been further challenged by unconventional reservoirs and associated well designs comprised of vertically deep and long horizontal wellbores, where production is commonly comprised of high gas to liquid ratios and high initial liquid rates but with associated high decline rates. Electrical submersible pumps and gas lifting artificial lifting system are commonly used during the initial high production rate phase but eventually the well is transitioned to lower operating expense (OPEX) sucker rod pumping. Being able to transition to rod pumping as early as possible and at the highest production rate possible often provides the most attractive well economics. Unfortunately, high-rate and deep rod pumping has been challenged by excessive failure frequencies, mostly related to sucker rod failures. It is apparent that a cost effective and high reliability solution for deep high-rate rod pumping is needed and therefore a better sucker rod is essential.

An ideal sucker rod for resolving current limitations and application challenges has been defined and characterized as follows:

1. High strength to weight ratio,
2. High tensile modulus,
3. High toughness and fatigue/endurance limit,
4. High corrosion tolerance,
5. High torsional stiffness and strength,
6. Cost comparable to low carbon steel alloys (i.e., KD rod), and
7. High ESG sustainability rating being recyclable and manufactured with a relatively low carbon footprint.

A composite material was identified, and it was hypothesized that it had the potential to satisfy the development of an ideal sucker rod. Unidirectional long fiber reinforced thermoplastic (FRTP) composite materials have gained significant attention in recent years due to their high strength/toughness, lightweight, excellent corrosion resistance, being partially recyclable with a relatively good lifecycle ESG rating and having comparable manufacturing costs to steel sucker rods.

The development of fiber reinforced thermoplastic (FRTP) sucker rods involves the integration of unidirectional high-performance long fibers, such as carbon or glass, into a semi-ductile thermoplastic matrix. This is vastly different from thermoset composites, which use a hard and relatively brittle epoxy matrix around the fibers. A major and unique feature of an FRTP composite rod is its remarkably high shear failure resistance and toughness as compared to a thermoset composite rod. A high shear failure resistance means the rods have compressional loading tolerance and the opportunity for an entire sucker rod string being comprised of FRTP sucker rods. The design process, prototyping/testing and recent well trials/results show promise for FRTP sucker rods. This paper explores the development of fiber-reinforced thermoplastic sucker rods as a encouraging alternative for overcoming the limitations of steel and thermoset fiberglass sucker rods.

SUCKER ROD LIFTING CHALLENGES

The most common form of artificial lift continues to be rod pumping or rod lifting, as it can offer a high production rate turn down ratio, high efficiencies, an ability to maximize production drawdown to the reservoir pressure and a lower cost of maintenance as compared to other forms of artificial lift.

Sucker rods are an essential and integral component for hydrocarbon wells, as they are used to transmit reciprocating motion from the surface to downhole reciprocating pumps for lifting produced liquids (oil and water) to the surface. Sucker rods are primarily made of steel alloys, which can exhibit reasonable durability and strength, but are susceptible to corrosion and fatigue failures. A low strength to weight ratio is also limiting for when deep and high production rate rod pumping is required. They are the most common cause of rod pumping failures and consequent high failure frequencies. Martinez[ii] compiled root cause of rod pumping failures in the middle continent area (Midcon) of the United States as in Figure 1.

Sucker rods made from steel are relatively heavy therefore require extensive well specific designs that taper rod strings diameters for optimizing the overall sucker rod string weight relative to the strength and fatigue requirements. Considerations are made for the dynamic loadings from accelerations and decelerations of the rods and fluids, frictional impacts, and to the structural/power limitations of the pump jack or unit at surface. Takacs[iii] discussed such sucker rod string design requirements for steel rod strings as shown in Figure 2.

Steels suffer from corrosion risks and corrosion can rapidly accelerate fatigue failures. Corrosion is often the root cause of sucker rod failures as was detailed by Fakher[iv], which includes a picture of a sucker rod corrosion failure as in Figure 3. Chilingar's[v] research showed how corrosion in an oilwell can accelerate fatigue failures and was described as in Figure 4.

Fiber reinforced composites (i.e., fibers surrounded by or wetted by a resin matrix) have gained considerable popularity as they can be tailored to have outstanding mechanical, thermal, and physical properties. Alam[vi] discussed these superior material mechanical properties over metals (steel and steel alloys) and is summarized in Figure 5. The fatigue behavior of composite materials and structures is complex since composites fail by a series of, or collection of damage mechanisms including fiber breakage, resin matrix cracking, fibre-matrix debonding, delamination and the effect of shear-induced damage on cracks. Fiber fracture is highly dependent on fiber strength and the resin matrix's mechanical properties. A resin matrix that is brittle will be more susceptible to crack formation as compared to a matrix resin that has ductility. Cracking can be slowed somewhat, if the reinforced fibers are of high stiffness or high tensile modulus of elasticity (such as carbon). This is because high stiffness and strength fibers can endure higher loads, which limits the strain in the system, and thus, of the resin matrix (under a given load).

Composite materials can beneficially offer a lower ESG environmental footprint over its entire lifecycle. They can require less energy to manufacture, which reduces CO_2 emissions. A high strength to weight ratio offers less energy consumption during operational use, further reducing CO_2 emissions. Composite materials can be recycled and reused.

Composite sucker rods, in the form of thermoset fiberglass sucker rods, have offered high strength to weight with greater corrosion resistance, potential for a reduction in the overall weight of a steel rod string by seven (7) times. But they can be too stretchy (i.e., have excessive elongation under stress) from a relatively low glass fiber tensile modulus of elasticity (approximately four times less than steel) for deep high-rate rod pumping and for when a high production rate decline is likely. Too stretchy of sucker rod string results in a large bottomhole pump stroke variability and irregular pump strokes as operating conditions change (i.e., changes in stroke rate, stroke length, pump intake pressures and fluid densities inside the tubing). This leads to inadequate downhole pump plunger space outs that cause reduced pump efficiencies. Too stretchy of rod string can also result in significantly less downhole pump plunger travel as compared to the pump jack's surface stroke, further reducing the pump's efficiency.

The reciprocating nature of a sucker rod pumping system in combination with the hydrostatic load transfer between the pump's standing and travelling valves each stroke, results in the lower part of the sucker rod string experiencing compressional and buckling loadings. Fakher[vii] described this cyclical condition in Figure 6.

Thermoset fiber glass sucker rods have a low failure tolerance to compressional and impact loads, forcing a larger proportion of a sucker string to remain as steel. Shear forces imparted to a sucker rod while under compression propagates rapidly propagates cracks through the brittle resin matrix and through fibers. They are also more costly than steel rods.

For sucker rod pumping, an ideal composite rod should possess properties that can tolerate compressional loads, has high impact resistance with a high fatigue endurance limit and an ability to limit or control crack formation (i.e., has a high resistance to failing in shear). A composite material that potentially offers these important sucker rod properties is fiber reinforced thermoplastic.

THERMOPLASTIC VERSUS THERMOSET FIBER REINFORCED COMPOSITES

A fibre reinforced composite material is comprised of two main components: fibers and resin matrix. The fibers are surrounded or "wetted" by the resin matrix. Alformet[viii] appropriately illustrates these basic components and configuration in Figure 7. The fibers can be comprised of virtually any fibrous material, but most commonly they are glass fibers (such as e-glass and s-glass) and carbon fibers.

In general terms, fiber-reinforced composite refers to the use of reinforcing fibers with a length of 1/4-inch or greater. These components increase mechanical properties, however, although they're technically considered fiber reinforced composites, their strength is not nearly comparable to that of continuous fiber-reinforced composites. Unidirectional and continuous long fiber reinforced composites offer the highest possible strength properties for axial tensile loading conditions, such as is expected for sucker rods.

Advances in thermoplastic and thermoset composite technologies are ongoing and there's most likely a place for both. While each has its own set of pros and cons, what ultimately determines which material is best suited to any given application comes down to several factors that may include any or all the following: strength, durability, fatigue behaviors, flexibility, ease/expense of manufacture, and reduced environmental impact with recyclability.

Figure 8 from The Madison Group[ix], shows thermoplastic polymer chains are not crosslinked together as in the case of thermoset composites. Thermosets form crosslinked polymer chains as the resin epoxy irreversibly cures or setups. Thermoset resins are primarily brittle epoxies. In a thermoset resin, the raw uncured resin molecules are crossed linked through a catalytic chemical reaction. Through this chemical reaction, most often exothermic, the resin molecules create extremely strong bonds with one another, and the resin changes state from a liquid to a solid. Thermoset polymers then form a highly cross-linked molecular irreversible structure when they cure. While these cross-links provide excellent thermal stability and chemical resistance, they also result in a rigid matrix that lacks the ability to deform plastically. As a result, when subjected to stress, thermoset composites are more likely to fracture or crack than to deform. A thermosetting resin, once cured, cannot be reversed or re-shaped, meaning, once a thermoset composite is formed, its shape cannot be altered. Because of this, the recycling of thermoset composites is extremely difficult. Thermoset resin itself is not recyclable[x].

Thermoplastic composites offer two major advantages for some manufacturing applications. The first is that many thermoplastic composites have an increased impact resistance to comparable thermosets. In some instances, the difference can be as much as 10 times the impact resistance. The other major advantage of thermoplastic composites is their ability to be rendered malleable (heated to the resin matrix's melting point). Thermoplastic polymers can be heated to their melting point and reformed to any shape and cooled back to solid multiple times. Raw thermoplastic resins are solid at room temperature, but when heat and pressure impregnate a reinforcing fiber, a physical change occurs (however, it isn't a chemical reaction that results in a permanent, nonreversible change). This is what allows thermoplastic composites to be re-formed and re-shaped. For example, you could heat a pultruded thermoplastic composite rod and re-mold it to have a curvature. Once cooled, the curve would remain, which is not possible with irreversible thermoset resins. This property shows tremendous promise for the future of recycling thermoplastic composite products when their original use ends.

Thermoplastic matrix resins are commonly a semi-crystalline ductile material, such as Nylon 6:6. Nylon 6:6[xi] is made of two monomers each containing 6 carbon atoms, hexamethylenediamine and adipic acid, which give nylon 66 its name. Aside from its superior physical characteristics, Nylon 6:6 is attractive because it is relatively inexpensive. More promising is the potential use of polyketone (PEK)[xii] as the matrix resin, as it is becoming a more common material for rod guides. PEK offers superior wear resistance in downhole conditions, as it possesses low water absorption as compared to nylon's – nylon water absorption reduces its mechanical properties includes wear/abrasion resistance. The mechanical properties stability and modification of properties of thermoplastic matrix resins can be substantially adjusted with addition of copolymers and other additives during manufacture.

By fully wetting the fibers in a thermoplastic matrix the apparent tensile strength of composite trends from statistical bulk behavior to molecular property behavior through better alignment of fibers on a microscale. See Figure 9 (source confidential), which shows that lowering fiber thickness of fully wetted (impregnated) provides exceptional strength properties. High elongation to break of the thermoplastic matrix resins does not allow the composite to fail in shear (the predominant premature failure mode of thermosets). This is seen as a shift of mean to higher tensile strength proportional to quality of wetting of fibers of material and better fiber alignment. Unidirectional continuous long fiber thermoplastic composites have material anisotropy, while mechanical properties in fiber direction may be very good, the properties at right angles to the fiber direction may be very poor (i.e., very bendable) and will almost certainly be different.

There are disadvantages of thermoplastic composites. While it can be made malleable through the application of heat, as the natural state of thermoplastic resin is solid, it's difficult to impregnate it with reinforcing fiber. The resin must be heated to the melting point and pressure must be applied to integrate fibers, and then, the composite must be cooled, all while still under pressure. Special tooling, technique, and equipment must be used, many of which are expensive. The process is much more complex and expensive than traditional thermoset composite manufacturing.

FATIGUE AND ENDURANCE LIMIT PROPERTIES OF FRTP COMPOSITES

Thermoplastic composites have an increased impact resistance to comparable thermosets. Luthada[xiii] showed that in some instances, the difference can be as much as 10 times the impact resistance. A ductile resin matrix resists crack formation and propagation. It can have unique characteristic that it can self-heal fatigue cracks and therefore greatly improve fatigue resistance.

Thermoset composites have a limited fatigue life. They have no physical endurance limit and therefore have a finite life under cyclic loading conditions due to inevitable resin crack formation and continuous fiber failure under cyclical loadings. Figure 10[xiv] shows various brittle crack formations/propagations in a fiber reinforced thermoset material and consequent fiber failure modes.

Since a thermoplastic matrix resin is semi-ductile, re-moldable and environmentally recyclable, the resin’s ductility allows for movement between fibers and therefore controls fatigue crack formation and propagation. This resin ductility provides a material with remarkably high shear failure tolerance.

Figure 11 shows a picture of a coiled 0.55” (14.0 mm) outside diameter FRTP sucker rod, using glass fibers. The rod is coiled into a six (6) foot diameter circle without damage, demonstrating its high toughness and resistance to shear failure. This could not be achieved with a thermoset sucker rod nor a steel sucker rod.

Figure 12 shows a confidential reference comparing fiber reinforced thermoplastic material fatigue versus thermoset. Thermoset materials continuously cyclically fatigue to failure and do not have an endurance limit. Whereas thermoplastic materials have a much greater fatigue tolerance in a more durable manner, holding their strength for upwards of 10,000,000 cycles, as an endurance limit, before showing signs of fatigue degradation.

Flexural stress is used in fiber composites because some fibers perform differently in compression and tension, so it is the more conservative of the two stress regimes that dominates the flexural performance. This important research suggests that 60% of the ultimate tensile stress (UTS) for a fiber reinforced thermoplastic material can be used as an endurance limit for up to 10,000,000 cycles.

USING FIBER REINFORCED THERMOPLASTIC COMPOSITES FOR SUCKER RODS

FRTP sucker rods offer several major advantages. Firstly, their lightweight nature reduces the overall load on the pumping system, leading to improved energy efficiency. This advantage is particularly beneficial for deep and/or high-angle wells. Secondly, the modulus of elasticity can be tailored to be equivalent to steel, avoiding challenges associated with fiberglass thermoset composite sucker rods being “too stretchy” for efficient and/or high production rate rod pumping. Thirdly, comparable costs to steel.

Thermoset fiberglass sucker rods have a low tensile modulus of elasticity as compared to steel, by approximately a magnitude of four (4) to five (5) times. From a sucker rod string performance perspective this relatively low modulus results in the sucker rods being “too stretchy” under tensile loads, especially if the well is deep (for example, 8,000 feet deep). Saponja[xv] in Figure 13 showed often that final operating parameters during rod pumping are unknown (for example, stroke rate per minute, annular fluid levels, fluid densities inside the tubing, production decline rates, etc). Consequently, the pump’s spacing and bottom hole stroke variability of a low modulus sucker rod string become considerable. Such variability results in pumping inefficiencies. Pump fillage can become erratic and cause erratic stress on the sucker rod string, reducing its service life.

An FRTP is light weight and can be even lighter than comparable fiber glass sucker rod. For example, an FRTP of 0.55 inches (14.0mm) in rod body diameter with metal end fittings, weighs 0.16 lbs/ft (0.24 kg/m). A 25-foot (7.6 m) long fully guided (6 guides per rod) FRTP rod with metal end fittings (without coupling) weighs only 11.1 lbs. This equates to a weight reduction ratio of 6.3 times that of an equivalent 1.0” (25.4 mm) diameter KD steel sucker rod.

A highly compelling and has shown potential in an FRTP sucker rod is being able to tolerate compressional and impact loads. The lower portion of a sucker rod string is subject to frequent compressional loadings and impact side loadings (i.e., rod slap). It is well known in the sucker rod community of practice that thermoset fiber glass rods are not able to tolerate compressional loads and therefore a high proportion of a sucker rod string must be comprised of steel rods; see Figure 6. Multiple literature sources discuss such beneficial material toughness features of fiber reinforced thermoplastic. Liu[xvi] revealed for low-velocity drop-weight tests, experimental results demonstrated that, at the same impact energy, the thermoplastic composites always possessed a superior impact performance as compared with thermoset composites.

For FRTP sucker rods and since glass fibers have a relatively low tensile modulus of elasticity (i.e., are too stretchy), it is preferable to use carbon fibers with a tensile modulus of elasticity equal to or greater than steel. In comparison, for example, a KD steel rod, a modified UNS G47200 nickel-chromium-molybdenum alloy steel has a Yield Strength of 85,000-90,000 psi (10% elongation) and tensile modulus of elasticity of approximately 30,000 ksi. Tables 1 and 2[xvii] show common steel sucker rod tensile loading working ratings and weights per rod respectively.

With carbon fibers, a FRTP rod can be stiffer (i.e., less stretchy) than a steel rod. Table 3[xviii] shows carbon fiber material properties used in the FRTP rods. It is not possible to attain the theoretical maximum UTS of all the fibers collectively together in an FRTP rod. This would only be possible if all the fibers were perfectly aligned and under the exact same strain through the cross section. As such, a percentage of the collective fibers UTS should be used and is typically 50% to 70%.

FRTP TORSIONAL STRENGTH AND STIFFNESS ADAPTABILITY

Sucker rod rotation during pumping is common practice. Rod rotation is primarily used to manage the risk of solids precipitation (paraffin, scale), erosional wear and corrosion. If solids precipitation occurs on the rods and/or tubing, the flow path can become restricted and the tensile loadings on the rods string can become excessive (due to increased friction), and rod fall could be inhibited due to increased frictional loads. If rods and their couplings are allowed to reciprocate in the same position repeatedly, the rods will wear eccentrically on one side and/or will wear a channel or “key “seat” in the tubing walls (leading to a loss of integrity hole in tubing). For corrosion, the wetted surface area of the metal tubing and rods can be worn off on the abrade contact area, which can lead to inadequate chemical corrosion protection and therefore more rapid corrosion.

Steel and metals most commonly behave as isotopic materials. In other words, in the X-Y-Z directions the material’s mechanical properties are the same. Torque capabilities of steel and steel sucker rods is well known and can be easily calculated.

For existing thermoset fiberglass sucker rods, manufacturers[xix] have shown 100 ft-lbs as the maximum allowable torque for fiberglass rods. This is relatively low in comparison for a 1.0“ (25.4 mm) KD steel rod, which is typically torque rated for a maximum allowable of 800 ft-lbs.

For long fiber composites, they have anisotropic material properties – how they behave in the X-Y-Z direction can be very different. For an FRTP rod with unidirectional long fibers oriented axially along the rod, the fiber orientation is intended to maximize tensile load capacities and not for torque capacity. Consequently, anisotropic mechanical properties occur. The fibers are “doing all the load work”, so the FRTP is very strong and stiff in the axial direction yet very flexible/bendable in the lateral direction (see Figure 11). This results in low torsional stiffness under torsional shear force loadings (i.e., it will easily twist up like a braided rope) in the range of only 10 ft-lbs to 20 ft-lbs for a 0.55" (14.0 mm) outside diameter FRTP rod.

To resolve FRTP's low torsional stiffness, the polar moment of inertia can be improved by an increase to the rod's diameter or fibers can be added or wrapped on to the outside diameter that are oriented in the radial direction (transverse to the axial direction of the unidirectional long fibers).

The structural reinforced concrete industry uses wrapping to improve the torsional stiffness of concrete members. Figure 14 from Askandar[xx] shows torque wrapping of a concrete structural member using twisted wire cable at a 45-degree angle relative to axial direction, designed to restrain torsional shear forces and avoid concrete cracking.

An example of increasing torque capacity of an FRTP rod is by using a pre-impregnated thermoplastic fiber wrapping and subsequently fusing it on to the FRTP rod through a pultrusion die during manufacturing – see in Figures 15 and 16.

Figure 17 shows a cut cross section of the resultant composite FRTP rod with torque wrapping.

Figure 18 shows torque testing to failure of FRTP torque wrapped rod. The design target torque capacities for the 0.55" and 0.75" FRTP rods are 150 ft-lbs and 400 ft-lbs respectively.

This ability to torque wrap and fuse together is a major advantage of FRTP composites, as additional torque wrapping can be added and therefore tailored for higher torque requirements at very little relative cost. This suggests FRTP sucker rods could be adapted to higher torque progressive cavity pumping (PCP's) applications.

Further FRTP radial wrapping advantages include that the external wrapping that can be tailored with resin additives for reducing the friction coefficient (targeting 0.1), for improving wear resistance and preventing solids precipitation adhesion.

FRTP SUCKER ROD END FITTING DESIGN

Thermoset fiberglass sucker rod end fittings have been continual challenge[xxi]. The fibers are cut at each end of the rod, so the end fitting must be able to engage all the fibers uniformly through the rod's cross section.

The design of FRTP sucker rod end fittings has been a considerable challenge. Fiber engagement through the entire cross section of FRTP rod is a challenge with a ductile resin matrix. A ductile behaving matrix resin limits conveyance of strain through the cross section of the FRTP and therefore attempting to restrain or affix an end fitting from just the outside diameter of an FRTP will result in the tensile load being contained and concentrated to the outer diameter fibers only – consequently, the end fitting will fail at a low tensile loading. A FRTP rod end fitting cannot just "hold on" from the outside diameter, so no gluing or bonding is possible as in the case of thermoset sucker rod end fittings.

Thermoset metal end fittings are glued on to the thermoset sucker rod. The brittle thermoset matrix allows for full transfer of strain through cross section of the rod and therefore engagement of all the fibers. Figure 19[xxii] shows a thermoset fiberglass rod end fitting and the gluing of the end fitting to the rod. The gluing process requires surface area to maximize the bond to the rod (i.e., gluing a larger surface area of rod distributes the load over a larger surface area. A such, thermoset fiberglass rods need to be and are commonly larger diameters for effective end fitting strength capacities.

Three years of extensive research and design and testing has achieved an end fitting full fiber through the cross section engagement and at relatively low cost. FRTP end fittings are subject to significant intellectual property and ongoing, so no details will be shared at the time of this paper.

Managing fiber orientation at end fittings was found to be a challenge. Any change in fiber angle relative to axial direction resulted in a localized stress concentration and below expectation tensile failures during testing. Figure 20 shows an early prototype FRTP end fitting design where a change in direction of the fibers resulted in an undesirable localized stress concentration. Unidirectional fiber angle changes or unbalanced strain pose stress riser risks, lower tensile loading failures and reduced fatigue endurance limits.

End fitting diameter comparison shows that FRTP end fittings can be smaller in diameter than for steel or thermoset sucker rods. Figure 21 shows an FRTP rod's metal end fitting at 1.5 inches outside diameter for an 0.55" (14.0 mm) FRTP rod.

ESG RATING OF FRTP SUCKER RODS

Designing an environmentally friendly sucker rod involves considering materials, manufacturing processes, and operational factors that reduce the environmental impact. Here are some key aspects to consider when designing such a rod.

FRTP sucker rods reduce CO_2 emissions as compared to conventional steels rods. Sbahieh's [xxiii] research revealed that fiber reinforced thermoplastics reduce the environmental impacts compared to traditional building materials like steel. They showed that the energy consumption used for making steel bars and beams was 50% higher than fiber reinforced composite bars and beams.

To maximize ESG rating, composite materials should use recycled or repurposed materials, when possible, to reduce the demand for new resources. FRTP sucker rods have recyclability, primarily through mechanical recycling. Pegoretti [xxiv] showed both thermoplastics and thermosets based composites can be shredded or crushed into particles or milled into fine powders. After this step, thermoplastic based composites can be reprocessed several times with the application of heat and pressure. On the contrary, recycled thermoset based composites can only be used as fillers, reinforcement or raw materials for cement, concrete, among others. In conclusion, FRTP at the end of their life cycle can be recycled and reprocessed back into new FRTP rods multiple times.

An FRTP sucker rod is a much lighter weight sucker rod as compared to steel, by 5 to 7 times. A FRTP sucker rod can lead to reduced energy consumption during pumping operations. FRTP rod string modelling has indicated a 30-40% reduction in pump jack energy requirements versus a rod string comprised of all steel sucker rods.

FRTP SUCKER ROD MANUFACTURING PROCESS

The FRTP sucker rods are manufactured in a four (4) primary stage process.

Stage 1 – Low Cost Rapid Prepreg. Purpose is to impregnate (100% wetted) individual raw fibers off a roving spool (containing 5000 to 8000 individual fibers) with heated and molten thermoplastic matrix resin. Prepregs are created by impregnating the selected fibers with thermoplastic matrix material. This step ensures the uniform distribution of fibers within the matrix, enhancing the overall mechanical properties of the rod. Consolidation of the wetted fibers into a single composite Prepreg thread and cool. Threads rolled onto individual spools. Figure 22 from Ning[xxv] illustrates the stage 1 process of fiber prepreg'ing and spooling of fully wetted fiber reinforced thermoplastic threads.

Stage 2 – Figure 23 shows the apparatus set-up for low cost FRTP rod consolidation. Multiple spool prepreg threads are fused into a 0.55" outside diameter round rod by pultruding through a heating/cooling die. This is a continuous process, where raw FRTP rods are then cut to desired lengths 25', 30', 37.5', 3' to 9' pony's or continuous rod of any length. Figure 23 also shows the FRTP raw rod exiting the consolation pultrusion die.

Figure 24 shows an example of cut cross sections of an inadequately consolidated rod. Fully consolidated refers to all the prepreg threads being fully fused together as a composite FRTP rod. Figure 25 shows an example of a cut cross section of adequately consolidated FRTP rod.

Stage 3 – Install Rod Guides and End Fittings, as shown in Figure 26. Thermoplastic rod guides are fused (melted) on to the rods. Metal end fittings are installed at working rating temperature and working rating tensile stress conditions.

Stage 4 - QC / QA Procedure. Rods are forced into a specified diameter circle prior to Rod Guides and End Fittings being installed – see Figure 11. Random section cutting (axial and transverse) and view under a microscope. After Rod Guides and End Fittings are installed, the completed rod is pull tested to working rating. Note low bending stiffness (anisotropic) equals considerably lower side loadings as compared to steel through wellbore dog leg severities.

FRTP FATIGUE AND ENDURANCE LIMITS

Kuwashiron[xxvi] describes fatigue is the progressive damage of a material when subjected to repeated cyclic loading. Even if a material is loaded at stress levels well below the elastic limit, under the conditions of continuous cyclic loading, microscopic damage occurs. This micro-damage accumulates throughout the material and can grow steadily into macro-cracks or may cause macro-scale damage leading to the ultimate failure of the material. Mechanical loading, thermal gradients, chemical ingress and environmental conditions all contribute to the rate at which fatigue damage occurs in materials. As such, fatigue is a complex process as the lifetime of a material under cyclic loading can be affected by many parameters in tandem.

An S-N fatigue curve, also known as a stress-life curve or Wöhler curve, is a graphical representation of the relationship between the applied stress (or load) and the number of cycles to failure in fatigue testing. It is a fundamental tool in materials science and engineering for evaluating the fatigue behavior of materials. The curve typically shows a logarithmic plot with stress (S) on the y-axis and the number of cycles to failure (N) on the x-axis. The S-N curve helps to define the fatigue limit, which is the stress level at which a material can endure an infinite number of cycles without failure. Below the fatigue limit, materials exhibit a long fatigue life, while above it, the number of cycles to failure decreases significantly. Understanding the S-N curve is crucial for designing and assessing the durability of a sucker rod and for prevention of fatigue-related failures.

Fatigue behavior in thermoset and thermoplastic composites differs primarily due to their resin matrix characteristics. Thermoset composites harden into a rigid, irreversible form when cured, which makes them more brittle and less resistant to fatigue compared to thermoplastics. Thermoset composites tend to exhibit limited fatigue resistance because their cross-linked polymer structure doesn't allow for molecular chain movement or self-healing of cracks under cyclic loading. This can lead to microcracks and eventual failure over time. In contrast, thermoplastic composites have a more flexible polymer matrix that allows for some degree of molecular chain movement. This gives them improved fatigue resistance as they can absorb and dissipate energy from cyclic loads, reducing the risk of fatigue-induced failure.

In Figure 27, Delmonte[xxvii] revealed that carbon fibers have excellent cyclical fatigue resistance as compared to steel, aluminum, and glass fibers. Concerningly, glass fibers continuously and rapidly fatigue and do not have a fatigue endurance limit.

The fatigue life behavior of thermoset fiberglass sucker rods completely differs from that of steel rods. The basic difference is that fiberglass rods have a finite life under cyclic loading conditions as was shown in Figure 27. The failure-free life of fiberglass thermoset rods varies not only with the range of stress, but also with the operating temperature. These are the reasons why API Specification 11B[xxviii] requires that manufacturers supply a basic stress range diagram for the fiberglass thermoset sucker rods they offer. This basic diagram should be constructed for a cycle number of 7.5 million (equal to 1.8 years of operation at a pumping speed of 8 SPM) and an operating temperature of 160 ^{o}F (71 ^{o}C).

Donnelly[xxix] showed in Figure 28 a modified Goodman diagram for steel and thermoset fiberglass sucker rods. Also shown in Figure 28 (in green) and using knowledge from Figure 11 previously regarding FRTP material superior cyclical fatigue performance, API

Modified Goodman Diagram (composites) the Endurance Limit for FRTP sucker rods has been set at T/1.67 (60% of UTS) versus T/3 or T/4 for steel and thermoset fiberglass sucker rods. This results in a carbon fiber FRTP 0.55" (14.0 mm) diameter sucker rod working rating of 35,000 lbs. These FRTP rods have a non-safety factored maximum allowable static stress load of 290,000 psi at a temperature of 200 ^{o}F (93 ^{o}C).

FRTP Fatigue Limits are allowable at a much higher ultimate tensile stress. FRTP = 200,000 psi (s-glass); 290,000 psi (carbon fiber), Thermoset Fiberglass = 120,000psi, Steel (KD) = 90,000 psi.

FRTP SUCKER ROD DEVELOPMENT TESTING AND COMMISSIONING

Extensive tensile testing to failure and fatigue testing has been conducted. Figure 29 shows the tensile testing apparatus.

Figure 30 shows a recorded test chart during a tensile loading test.

Figure 31 shows temperature testing under various load conditions. Assessing creep risks at elevated temperatures confirms FRTP sucker rods can be higher temperature tolerant. Temperature testing and determining rating up to 200 ^{o}F.

Figure 32 shows cyclical fatigue testing at SSI's hydraulic pump jack facility in Calgary, Alberta, Canada.

FRTP SUCKER ROD FAILURE AND WELLBORE FISHING AND RECOVERY CONSIDERATIONS

FRTP sucker rod tensile and compressional failures were extensively conducted and analyzed. Long term concerns have been recorded with thermoset fiberglass sucker rods failing in a "broom sticking" manner, which have resulted in costly fishing and workover costs. Figure 33 shows a thermoset fiber glass rod failure.

Failure mechanisms for fiber reinforced thermoplastic members were detailed by Danzia[xxx] and is shown in Figure 34. A relatively clean break across the FRTP rod section. A ductile resin matrix can absorb and dissipate failure energy more effectively and therefore avoids thermoset "broom sticking" due to high crack propagation toughness of ductile matrix. This suggests a lower wellbore fishing risk than thermoset composites.

Figure 35 shows a 0.75" square shaped FRTP rod test to failure. In this example, a compressional failure was recorded with a relatively clean break at approximately 10,000 lbs of unsupported compressional load.

Figure 36 shows 0.55" round shaped FRTP rods tested to failure (with the proprietary end fitting) under tensile loadings. Very consistent, clean break and uniform localized failures (i.e., minimal broom sticking).

FRTP SUCKER ROD GUIDE DESIGN

Designing and applying sucker rod guides are important aspects of rod pumping. Sucker rod guides are used to guide the sucker rods in and out of the wellbore, reducing frictional loadings, control rod buckling, and controlling paraffin deposition. For existing steel and thermoset fiberglass sucker rods, rod guides are primarily applied for controlling wear on the rod bodies, the end fittings, and the couplings. They also reduce wear and friction on the tubing and can manage excessive rod side loading through high dog leg severities and high well bore inclinations. For complex rod harmonics, rod guiding can be used to reduce damaging rod slapping and impact loadings.

A heavy steel rod string can have very-high rod side loadings through dog leg severities in a wellbore. Traditional rod guides are therefore designed for controlling the risks associated with high side loadings associated wear from high normal forces.

Fluid flow friction across traditional rod guides for the FRTP sucker rods was a concern and risk. Traditional rod guides are commonly 2-dimensional and restrict the annual flow path to the tubing. Excessive fluid flow friction and consequent pressure losses impose a piston effect across annular flow by restrictive rod guides. A piston effect resists sucker rod motion up or down. This piston effect has not been a concern with heavy steel rod strings, as their overall weight overwhelms or counters any negative impacts to rod fall performance (in most applications). In some cases, adding sinker bars or sinker rods can counter this effect.

FRTP rod guides design principles are more focused on controlling rod fall efficiency and controlling sucker rod buckling, as opposed to controlling high side loading. A very light weight rod string with very flexible sucker rods results in rod side loadings that are considerably less as compared to steel rod string. Less side loading also equates to less overall mechanical friction in the system.

Such a traditional rod guide flow path restriction acts like a piston effect for each rod guide, which adds up to considerable amount of fluid flow friction for when considering a relatively lightweight sucker rod string. This may be acceptable for a heavy steel-based rod string but for a lightweight FRTP string, it could prevent the rods from falling or grossly reduce the rate at which rods fall during the pump’s downstroke. As such traditional and conventional rod guides were deemed not compatible with FRTP sucker rods.

FRTP rod guides were designed using a tear drop shape and 3-dimensionally positioned blades. The design intent is to bias minimization of fluid friction in the rod fall direction. A tear drop shape has nature’s lowest coefficient of friction as shown in Figure 37[xxxi].

Figure 38 shows the design of the proprietary FRTP sucker rod guide.

FRTP COMPOSITE SUCKER ROD DESIGN SPECIFICATIONS

See Figure 39 for a picture of an example completed sucker rod. The initial commercial FRTP sucker rod offerings will be of two rod diameters of 0.6” (15.2 mm) and 0.8” (20.3 mm), including a radial torque wrap.

Shallow and lower production rate well FRTP sucker rods:

- Length: 25 feet or 30 feet plus variable length pony rods
- Rod Diameter: 0.6”
- Rod Guides: 6 FRTP guides per sucker rod
- Weight: 11.1 lbs per 25-foot-long rod (0.44 lbs/ft)
- End Fitting: 1.5” OD, API 0.75” thread, metal (4320 or 17-4 PH 1150)
- Modulus of Elasticity: carbon fiber at 35 msi or glass fiber at 7 msi
- Tensile, working (at 200 ^oF): 35,000 lbs (carbon fiber) or 25,000 lbs (glass fiber)
- Torque, working (at 200 ^oF): 100 ft-lb torque

Deep and higher production rate well FRTP sucker rods:

- Length: 25 feet or 30 feet plus variable length pony rods
- Rod Diameter: 0.8”
- Rod Guides: 6 FRTP guides per sucker rod
- Weight: 14.0 lbs per 25-foot-long rod (0.56 lbs/ft)
- End Fitting: 1.9” OD, API 1.0” thread, metal (4320 or 17-4 PH 1150)
- Modulus of Elasticity: carbon fiber at 35 msi or glass fiber at 7 msi
- Tensile, working (at 200 ^oF): 50,000 lbs (carbon fiber) or 35,000 lbs (glass fiber)
- Torque, working (at 200 ^oF): 400 ft-lb torque

When a rod is subjected to stress, a proportionate amount of strain with associated elongation is produced. For a carbon fiber FRTP sucker rod to stretch similarly under a weight corrected rod string load as a 1.0” KD steel rod (in a deeper well application), the FRTP rod diameter would need to be approximately 0.75”.

ENERGY EFFICIENCY AND SAVINGS OF AN FRTP SUCKER ROD STRING

Hale[xxxii] provided a useful analysis describing the benefits and great value of thermoset carbon fiber sucker rods. Unfortunately, adoption of these rods has not occurred. Challenges with a high cost per sucker rod relative to steel rods is believed by the authors to be the root issue.

FRTP sucker rods offer numerous operational benefits. In the case for a typical Permian basin well (Martin County equivalent):

- cost comparable to mechanically equivalent steel rods

- opportunity to use smaller pump jacks (less cost and energy usage), see Figure 40 showing Conventional rod string with a 912 pumpjack is equivalent to a FRTP rod string with a 640 pumpjack,
- increase displacement capacity with existing pump jack, see Figure 41 showing pump jack displacement comparison of a FRTP sucker rod string,
- decrease in sideload due to weight reduction, see Figure 42, FRTP sucker rods reduce side loadings by 40% over steel,
- decrease in energy consumption due to weight and friction reduction, and
- decrease in rod failure frequency.

Figure 40 illustrates a typical fiber glass and steel rod string with sinker bars/rods on the bottom. It also illustrates an FRTP rod string with sinker bars/rods on the bottom. Ideally, rod designs aim to place the whole rod string under tension during the entire pumping cycle/stroke. The advantages of using sinker bars or sinker rods in a thermoset fiberglass and steel rod string are the elimination of compressional loading risks in lower rod sections. For thermoset fiberglass and steel rod strings, the steel section of rods is used to avoid the risk of any rod compressional loadings in the thermoset fiber glass rods. Since production rates are constantly declining, it is very difficult to design a rod string that will always avoid compressional loads. This design process is much more complex with stretchy thermoset fiberglass rods in the top portion of a rod string and therefore more “safety factored” steel rods are run above the sinker bars/rods to compensate. For an FRTP rod string, periodic compressional loads are acceptable, so only sinker bars/rods are required in the lowermost portion of the rod string.

FIELD TRIAL

Successful first field trial. Permian well with 4-foot-long pony rods using prototype metal end fittings and square shaped FRTP rod. See Figures 43 and 44. Rod string location cyclical tensile loadings of the two pony FRTP rods were approximately maximum 20,000 lbs and 12,000 lbs and minimum loadings of 13,000 lbs and 5,000 lbs respectively. In well test period was 40 days total time recording approximately 250,000 cycles. No end fitting failures or FRTP rod degradation were recorded.

CASE STUDIES

Field implementations of partial to full length FRTP rod strings are planned through Q2 and Q3 of 2024, with manufacturing scale up and commercial availability sometime there after. Results to follow.

CONCLUSIONS

The development of FRTP sucker rods represents a promising alternative to conventional steel rods in the oil and gas industry. Their resistance to corrosion, durability with compressional load tolerance, weight reduction, and improved efficiency makes them a viable option for challenging well environments. They offer a solution for deep high-rate rod pumping and an earlier transition to rod pumping from ESP pumping or gas lifting. Further research and field testing are needed to refine the design and optimize their performance, but the potential benefits are substantial.

However, several FRTP sucker rod challenges exist. Manufacturing processes must be optimized to achieve consistent fiber-matrix distribution and fusing consolidation. An end fitting design that maximizes unidirectional fiber engagement with uniform strain and with creep control has required considerable research and design. While challenges remain, ongoing research and advancements in materials and manufacturing techniques are paving the way for the near-term commercialization of FRTP sucker rods.

Conclusions on FRTP sucker rods:

1. Showing promise to significantly improve rod pumping performance and replace steel rods.
2. Opportunity for lowering energy costs and OPEX.
3. Opportunity to improve ESG rating.
4. Offer a clear line of sight for achieving our mission.

Going forward plans:

1. Multiple and extensive field trials.
2. Commercial availability targeted for the third quarter of 2024.
3. Development of full thermoplastic end fittings and field repairable FRTP rods.
4. Development of continuous FRTP rods.

FIGURES

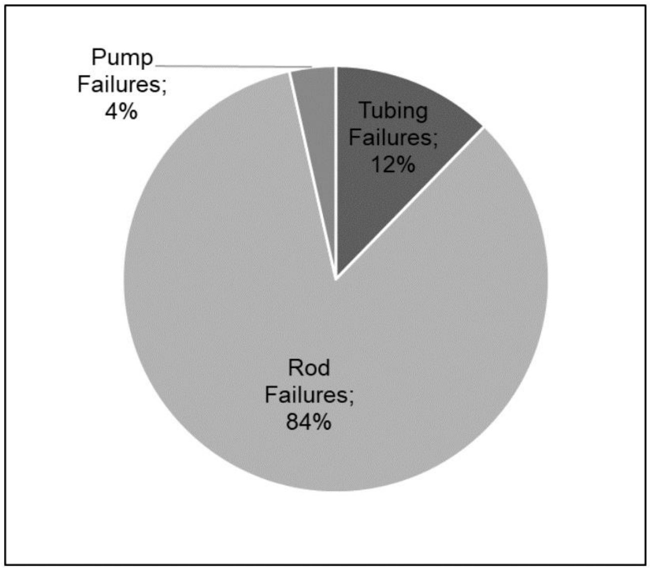


FIGURE 1 – SUCKER ROD PUMPING FAILURE FREQUENCIES ARE MOST CAUSED BY SUCKER ROD FAILURES

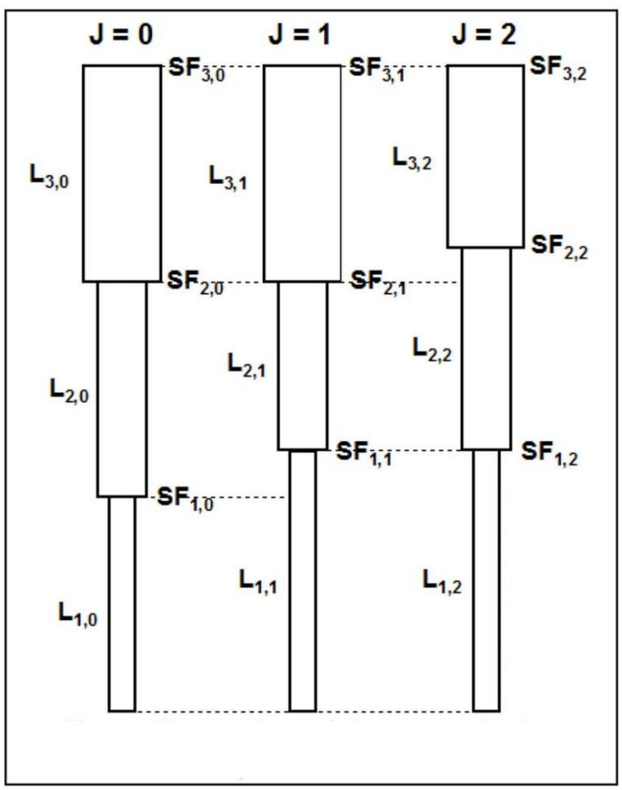


FIGURE 2 – TAPERING OF STEEL SUCKER ROD STRINGS DUE TO STEEL HIGH OVERALL WEIGHT

FIGURE 3 – STEEL SUCKER ROD CORROSION AND CORROSION RELATED FATIGUE FAILURE

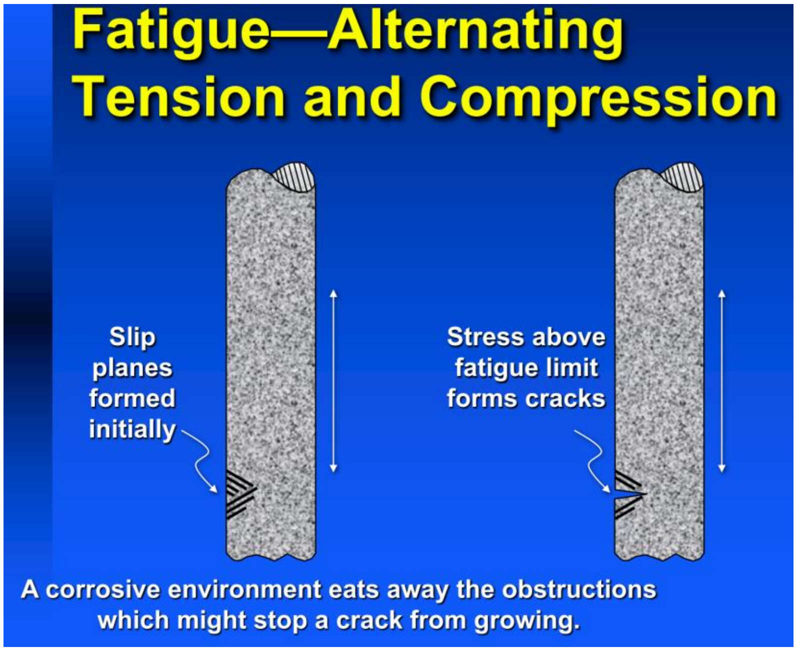


FIGURE 4 – CORROSION OF STEEL CAN ACCELERATE FATIGUE FAILURES

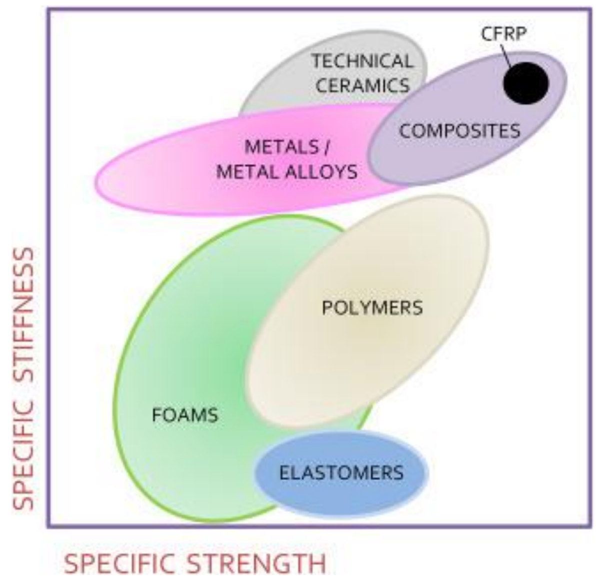


FIGURE 5 – COMPOSITE MATERIALS CAN OFFER SUPERIOR MECHANICAL PROPERTIES AND PERFORMANCE TO METALS

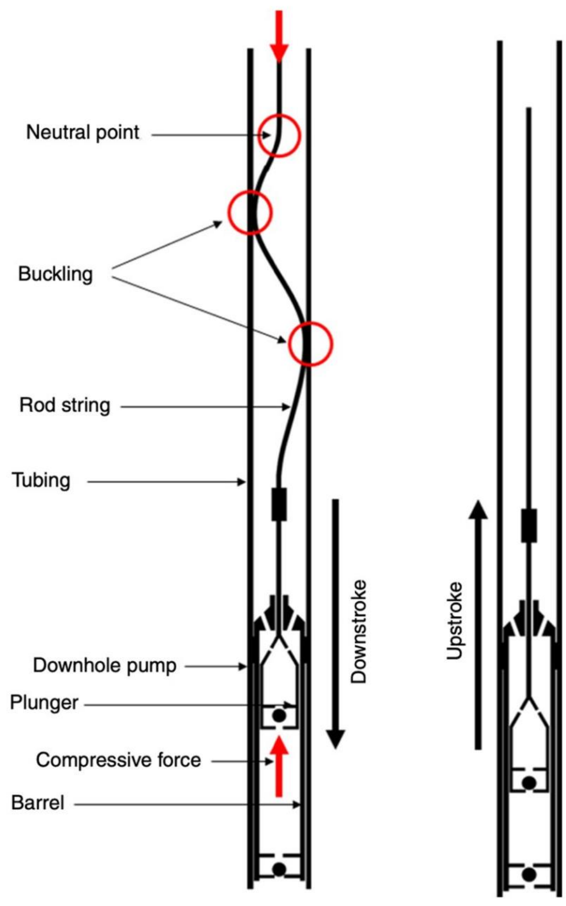


FIGURE 6 – COMPRESSIONAL ROD STRING LOADINGS IN THE LOWER PORTION OF A ROD STRING EACH PUMP STROKE

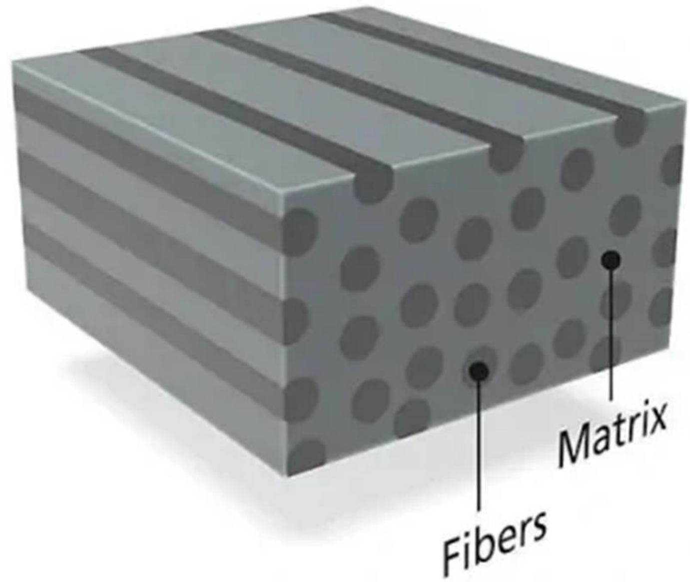


FIGURE 7 – FIBER REINFORCED COMPOSITE IS COMPRISED OF FIBERS SURROUNDED OR "WETTED" BY A RESIN MATRIX

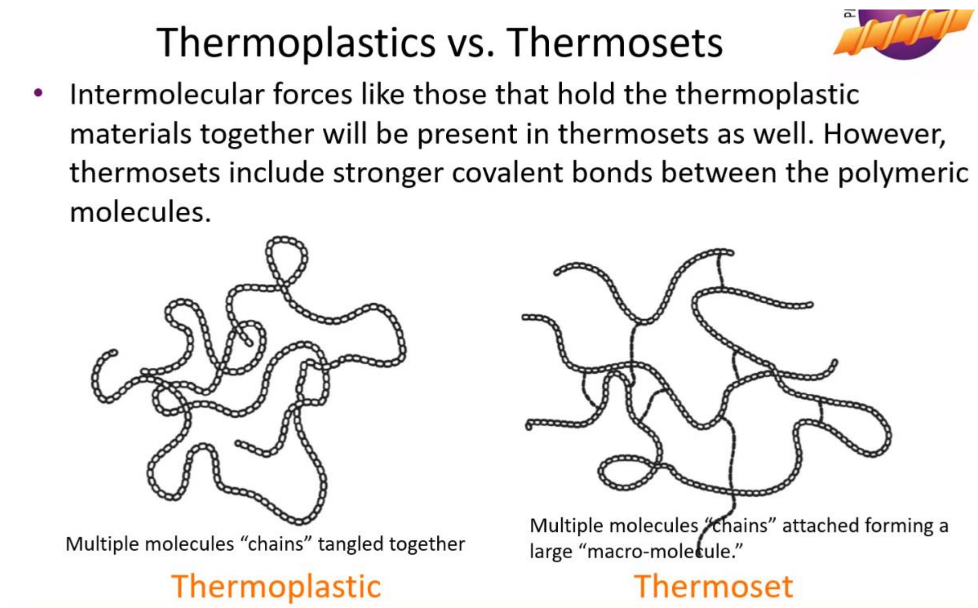


FIGURE 8 – THERMOPLASTIC VERSUS THERMOSET FIBER REINFORCED COMPOSITES

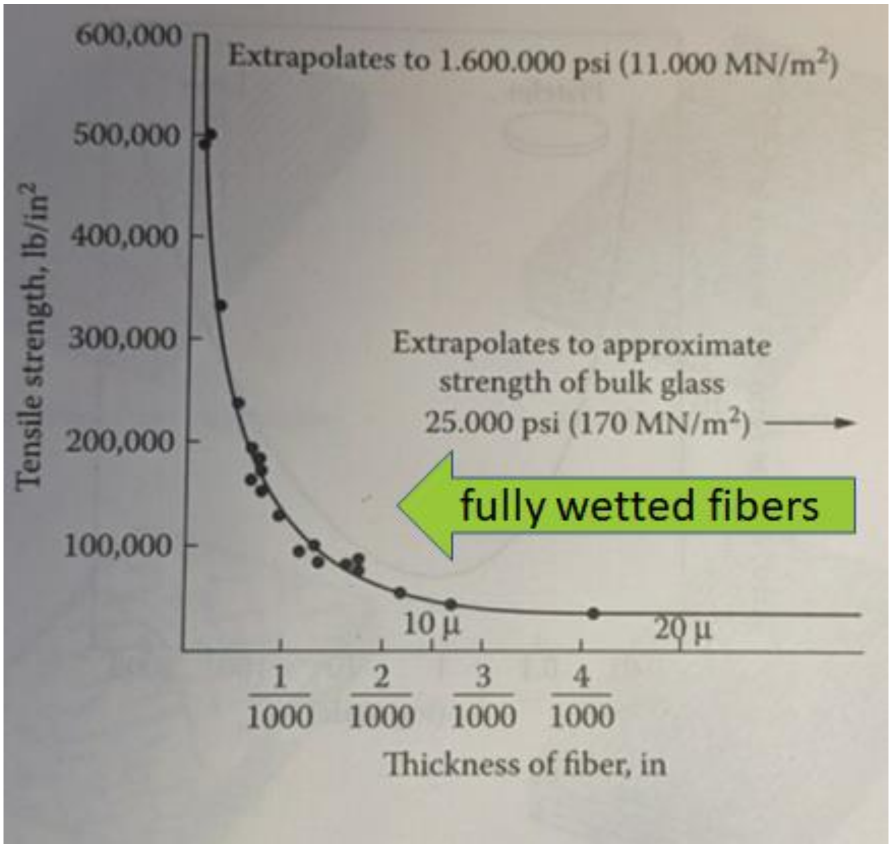


FIGURE 9 – FIBER THICKNESS VERSUS THERMOPLASTIC COMPOSITE STRENGTH OF FULLY WETTED FIBERS

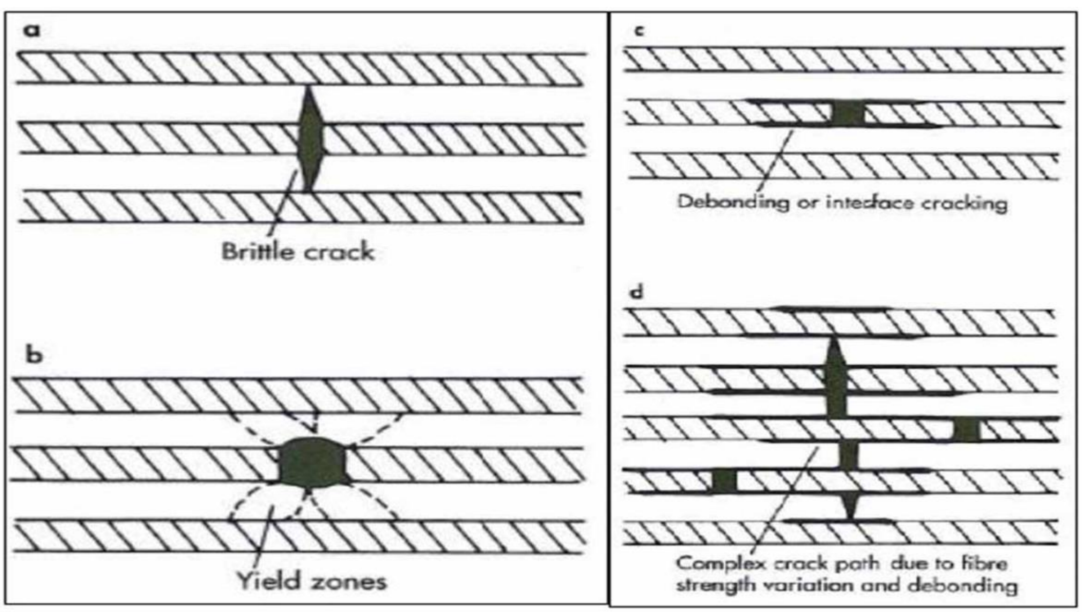


FIGURE 10 – THERMOSET COMPOSITES CONTINUOUSLY HAVE CRACK FORMATION AND PROPAGATION RESULTING IN A LIMITING FATIGUE LIFE

FIGURE 11 – COILED FRTP SUCKER ROD, DEMONSTRATING HIGH SHEAR FAILURE TOLERANCE

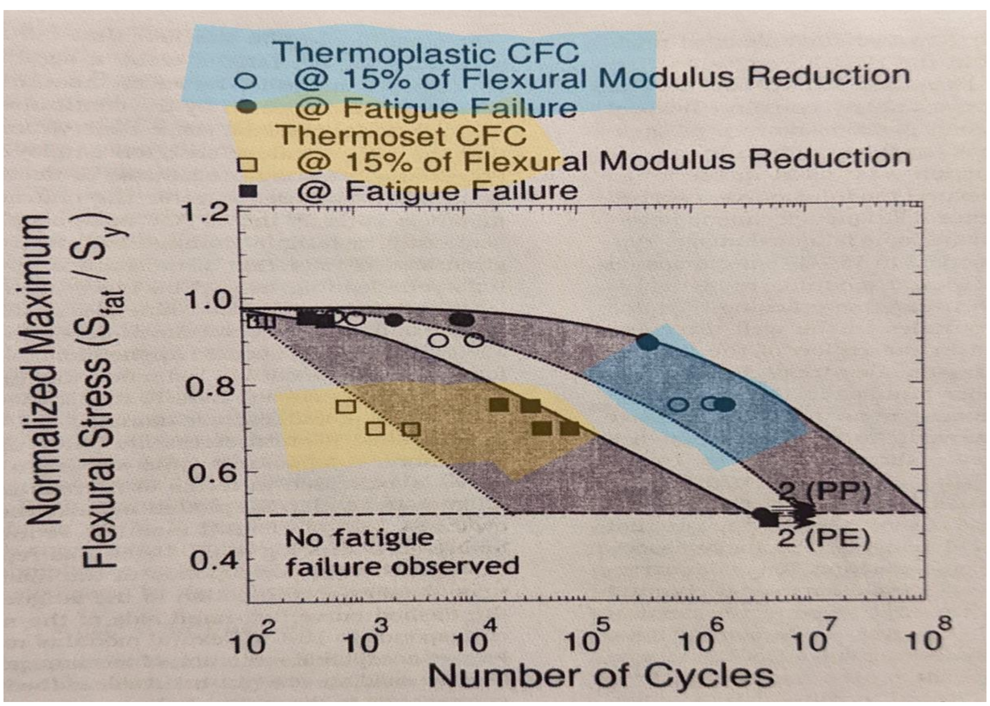


FIGURE 12 – CYCLICAL FATIGUE PERFORMANCE DIFFERENCE BETWEEN THERMOPLASTIC AND THERMOSET FIBER REINFORCED COMPOSITES

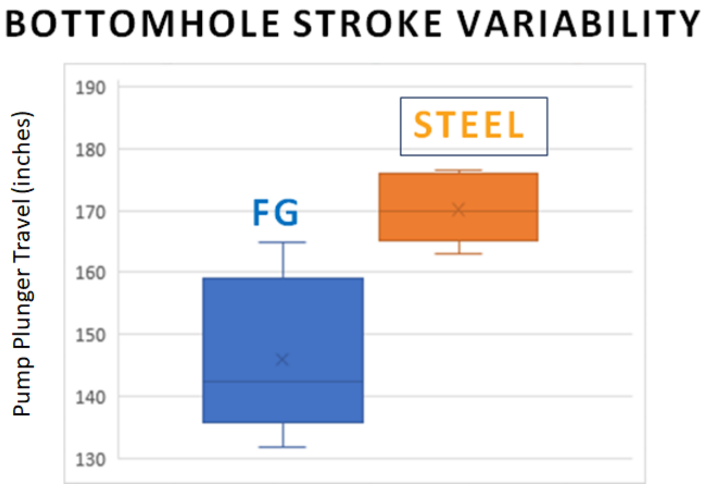


FIGURE 13 – BOTTOMHOLE PUMP STROKE VARIABILITY OF STEEL VERSUS THERMOSET FIBERGLASS SUCKER RODS

Rod Type	Size (in.)	Load	
		(lb)	(DaN)
KD	3/4	37,700	16,800
	7/8	51,400	22,800
	1	67,100	29,800
	1-1/8	84,900	37,700

TABLE 1 – STEEL KD SUCKER RODS TENSILE LOADING WORKING RATINGS

Approximate Weight of 25-ft Sucker Rod

API Size (in.)	Without Coupling (lb, kg)	With Standard Coupling (lb, kg)	With Slimhole Coupling (lb, kg)
5/8	27.2 12.3	28.5 12.9	28.2 12.8
3/4	38.5 17.5	40.0 18.1	39.8 18.1
7/8	52.0 23.6	53.8 24.4	53.5 24.3
1	69.9 31.7	72.5 32.9	71.9 32.6
1-1/8	88.7 40.2	91.8 41.6	91.17 41.35

TABLE 2 – STEEL KD SUCKER ROD WEIGHTS

Typical Fiber Properties	U.S. Units	SI Units
Tensile Strength	715 ksi	4930 MPa
Tensile Modulus (Chord 6000-1000)	35.3 Msi	243 GPa
Ultimate Elongation at Failure	1.8%	1.8%
Density	0.0647 lb/in^3	1.79 g/cm^3
Weight/Length (12K)	44.8 x 10^{-6} lb/in	0.800 g/m
Approximate Yield (12K)	1,860 ft/lb	1.25 m/g
Tow Cross-Sectional Area (12K)	6.93 x 10^{-4} in^2	0.45 mm^2
Filament Diameter	0.271 mil	6.9 microns

TABLE 3 – CARBON FIBER PROPERTIES

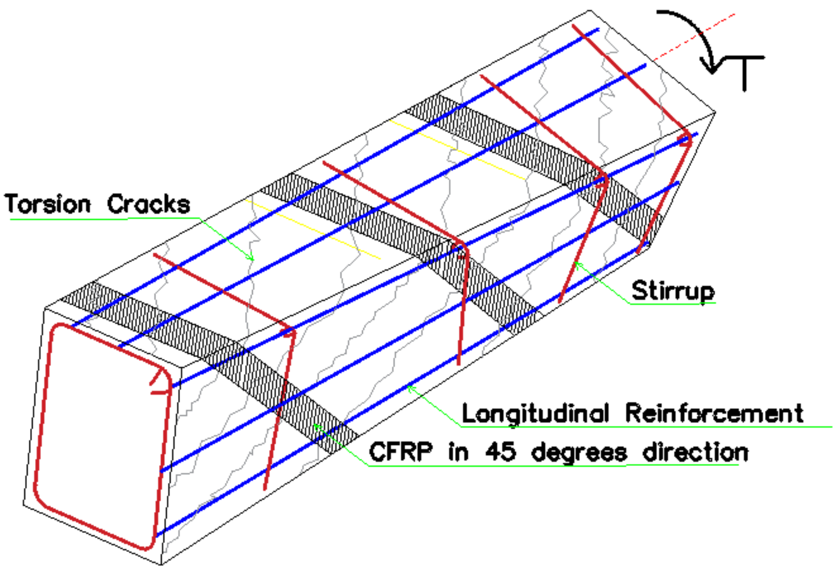
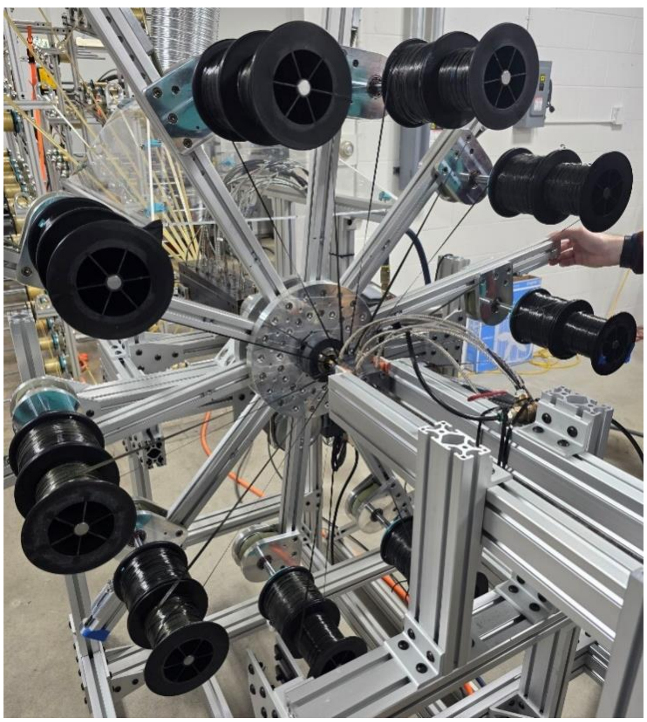


FIGURE 14 – STEEL WIRE TORQUE WRAPPING OF A CONCRETE MEMBER



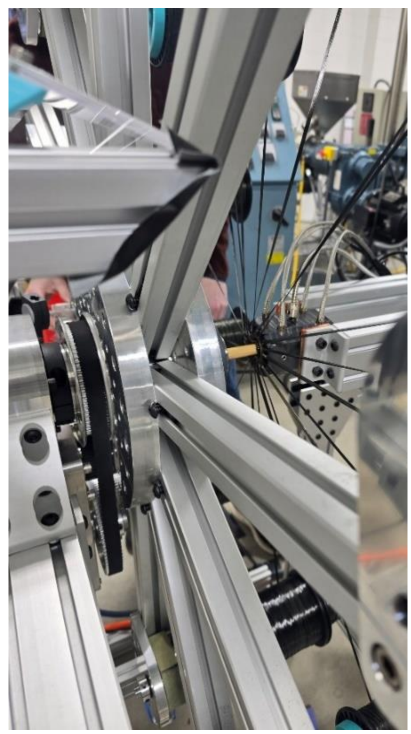


FIGURE 15 – RADIALTORQUE WRAPPING AN FRTP ROD FOR INCREASED TORQUE CAPACITY

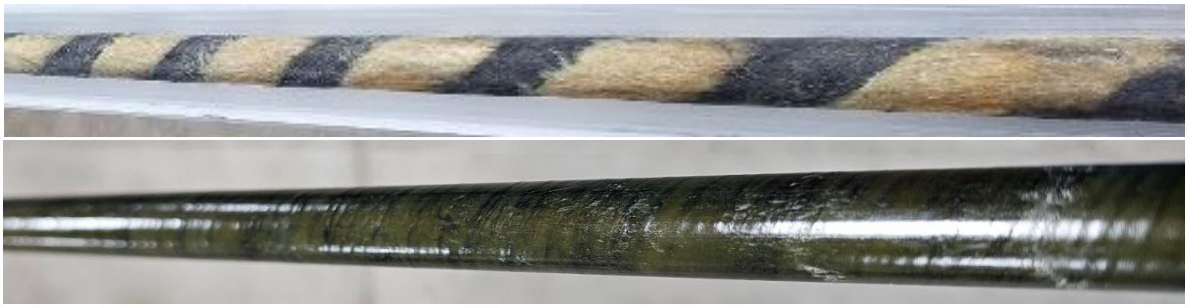


FIGURE 16 – RADIAL TORQUE WRAPPED FRTP RODS

FIGURE 17 – CUT CROSS SECTION OF A RADIAL TORQUE WRAPPED FRTP ROD

FIGURE 18 – FRTP ROD TORQUE FAILURE TESTING

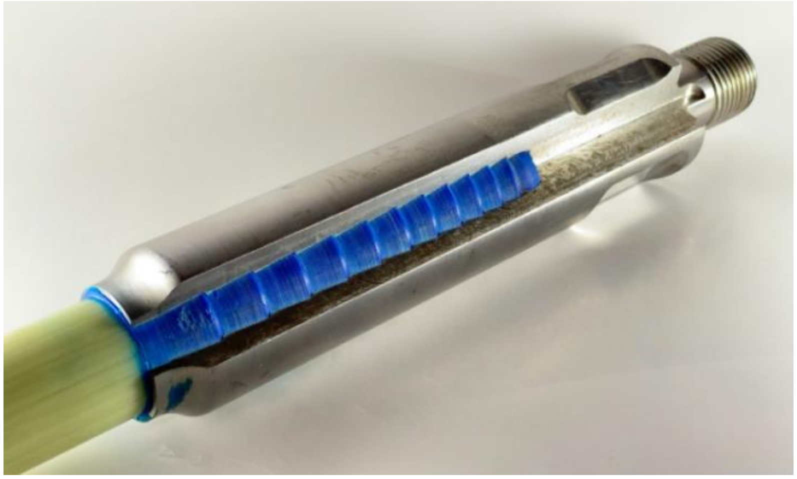


FIGURE 19 – THERMOSET FIBER GLASS SUCKER ROD GLUED OR BONDED ON METAL END FITTING

FIGURE 20 – THERMOPLASTIC FIBER ORIENTATION STRESS CONCENTRATION FAILURE IN AN EARLY-PHASE PROTOTYPE END FITTING

FIGURE 21 – 1.5" (38.1 MM) DIAMETER FRTP SUCKER ROD METAL END FITTING WITH AN API CONNECTION THREAD

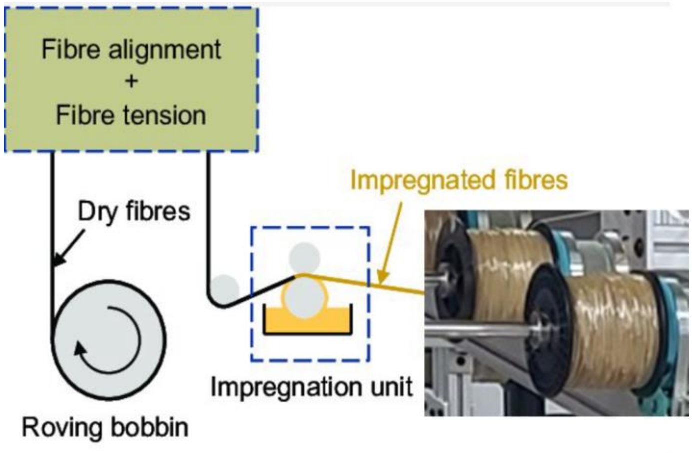


FIGURE 22 – STAGE 1 OF MANUFACTURING: LOW COST AND RAPID PREPREG THREAD MANUFACTURING

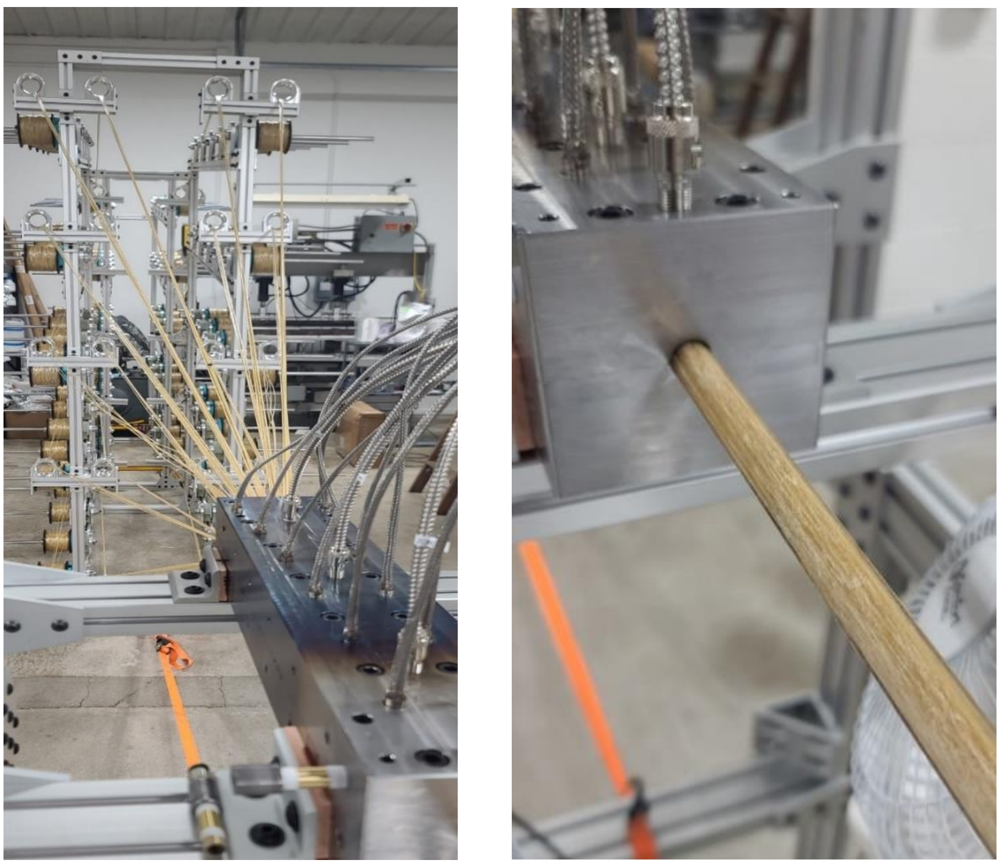


FIGURE 23 – STAGE 2 OF MANUFACTURING: LOW COST FRTP RAW ROD CONSOLIDATION USING PULTRUSION THROUGH A HEATING/COOLING DIE

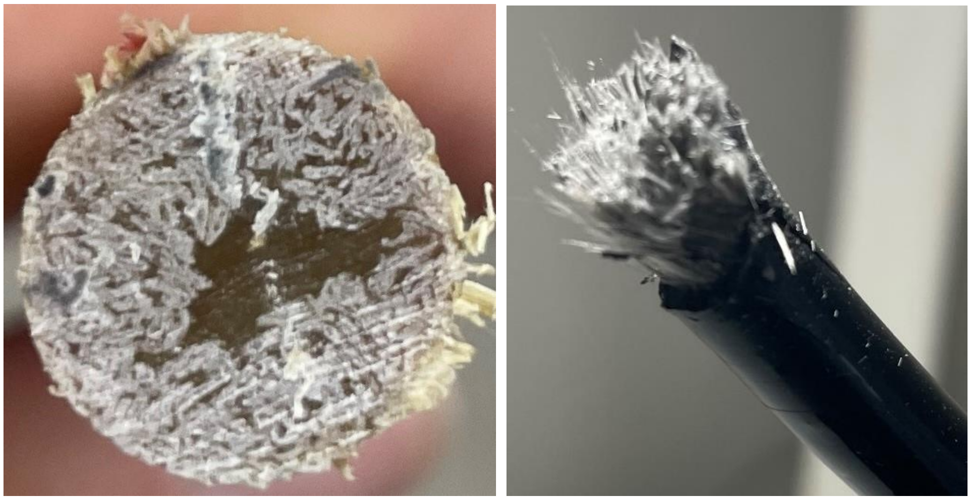


FIGURE 24 – INADEQUATELY CONSOLIDATED FRTP ROD

FIGURE 25 – ADEQUATELY CONSOLIDATED FRTP ROD

FIGURE 26 – STAGE 3 OF MANUFACTURING: INSTALLATION OF THERMOPLASTIC ROD GUIDES AND METAL END FITTINGS

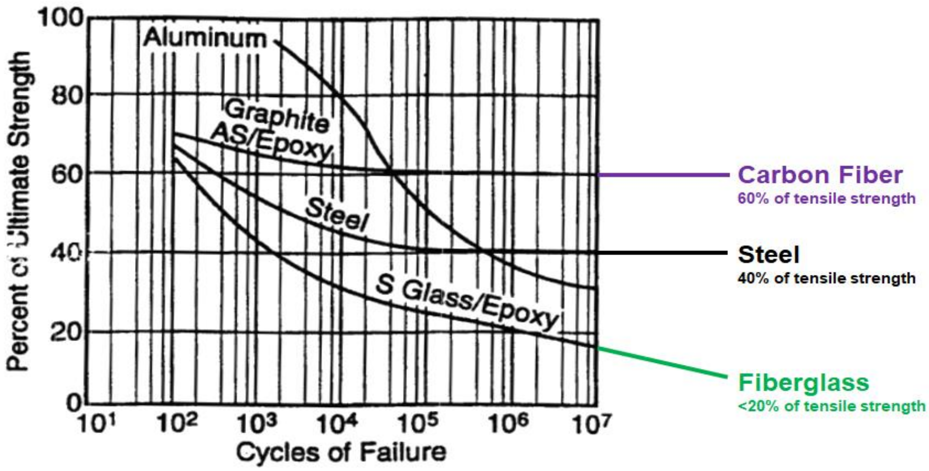
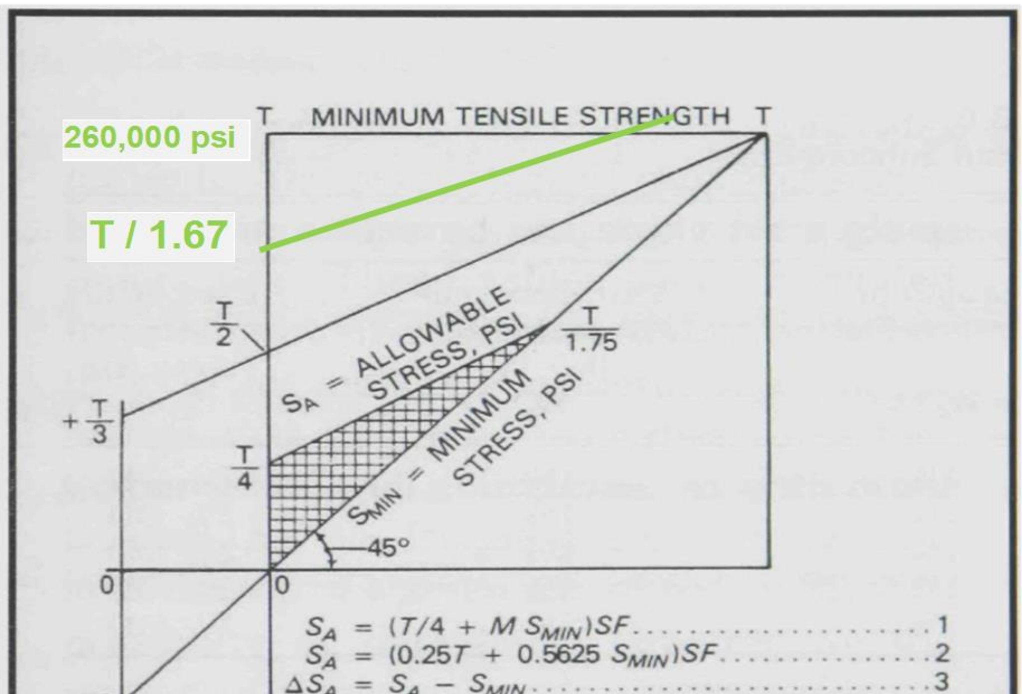


FIGURE 27 – CYCLICAL FATIGUE LIMITS OF FIBERS AS COMPARED TO STEEL



$S_A = (T/4 + M\, S_{MIN})SF$ 1

$S_A = (0.25T + 0.5625\, S_{MIN})SF$ 2

$\Delta S_A = S_A - S_{MIN}$ 3

where

S_A = maximum allowable stress, psi
ΔS_A = maximum allowable range of stress, psi
M = slope of S_A curve = 0.5625
S_{MIN} = minimum stress, psi (calculated or measured)
SF = service factor
T = minimum tensile strength, psi

FIGURE 22 – MODIFIED GOODMAN DIAGRAM FOR REPRESENTATION OF CYCLICAL FATIGUE LIMITS FOR FRTP SUCKER RODS

FIGURE 29 – FRTP SUCKER ROD AND END FITTING TENSILE TESTING APPARATUS.

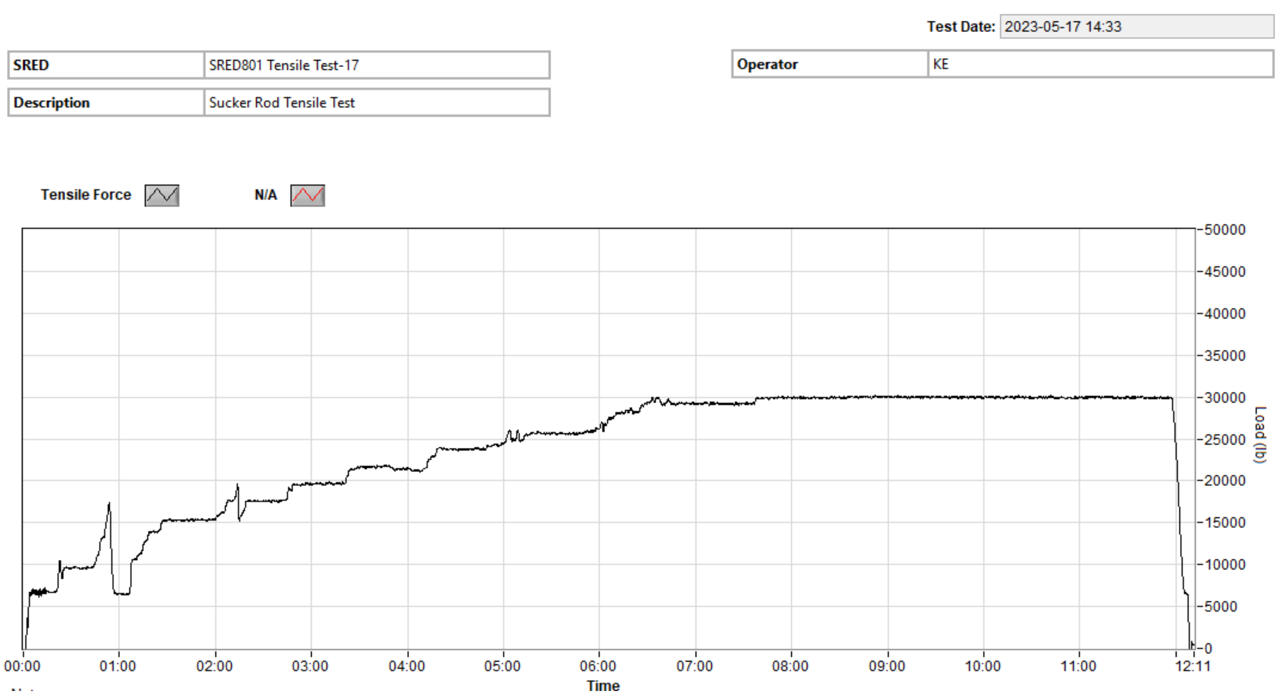


FIGURE 30 – EXAMPLE FRTP SUCKER ROD AND END FITTING TENSILE TESTING RECORDED RESULTS

FIGURE 31 – EXAMPLE FRTP SUCKER ROD TEMPERATURE AND CREEP LOAD TESTING

FIGURE 32 – EXAMPLE FRTP SUCKER ROD AND END FITTING FATIGUE TESTING (SSI CALGARY YARD)

FIGURE 33 – EXAMPLE THERMOSET FIBERGLASS SUCKER ROD FAILURE AND "BROOM STICKING" FAILURE MECHANISM.

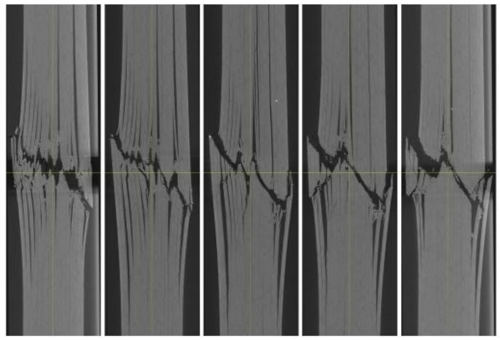


FIGURE 34 – FRTP FAILURE MECHANISMS, SHOWING RELATIVELY CLEAN AND "FISHABLE" BREAK

FIGURE 35 – FRTP FAILURE TESTING UNDER COMPRESSIONAL LOADING

FIGURE 36 – FRTP FAILURE TESTING UNDER TENSILE LOADING

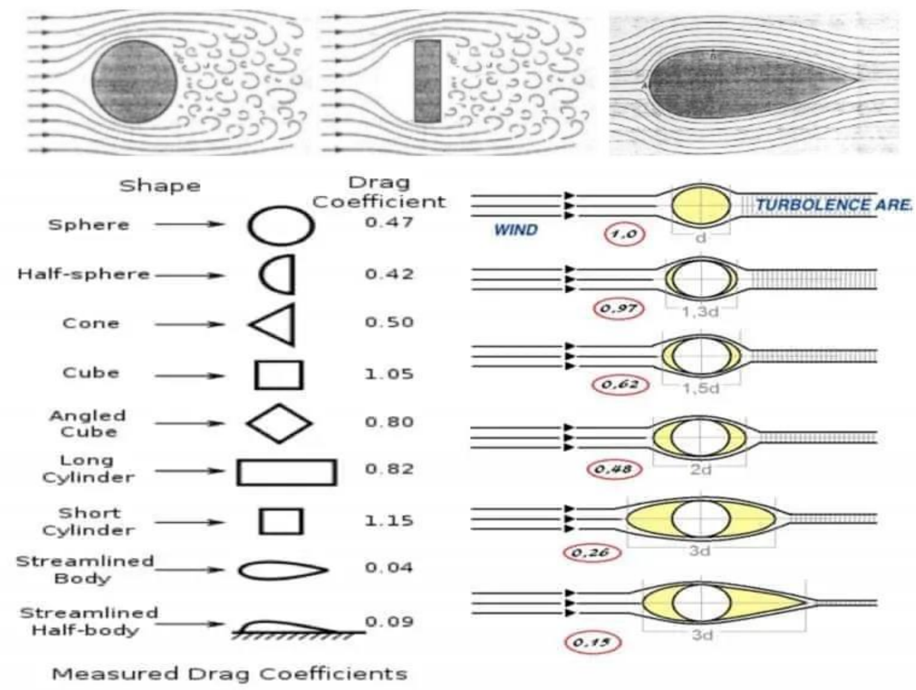


FIGURE 37 – FLUID FLOW DRAG AND COEFFICIENTS AS A FUNCTION OF OBJECT SHAPE

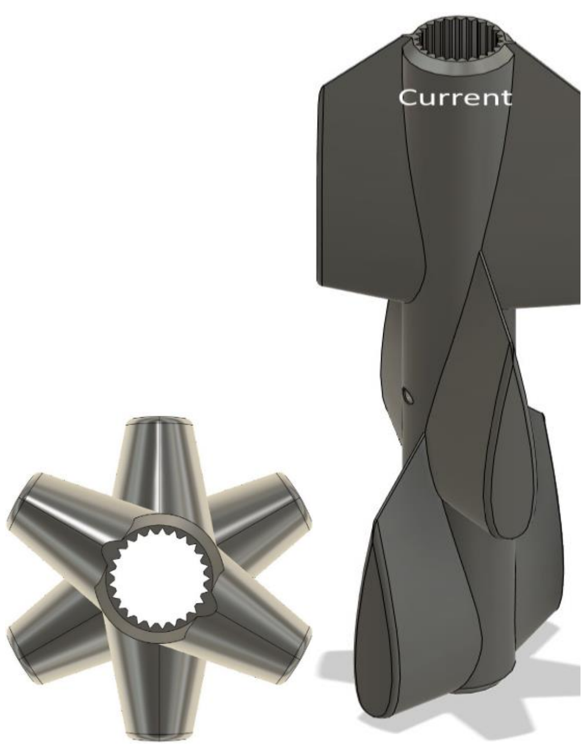


FIGURE 38 – FRTP SUCKER ROD GUIDE DESIGN USING 3-DIMENSIONAL TEAR DROP SHAPE TO FAVOUR ROD FALL

FIGURE 39 – COMPLETE FRTP SUCKER ROD

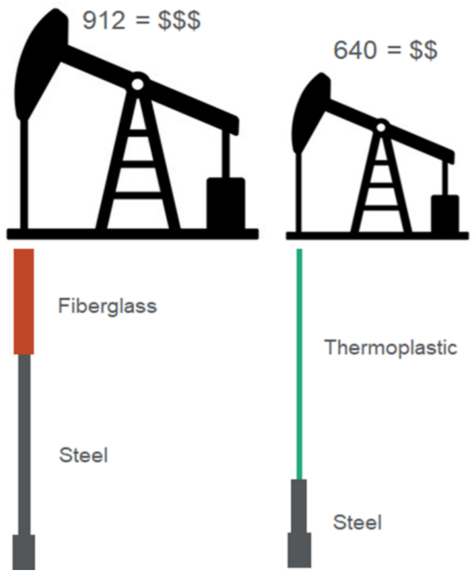


FIGURE 40 – CONVENTIONAL ROD STRING WITH 912 PUMPJACK IS EQUIVALENT TO A FRTP ROD STRING WITH 640 PUMPJACK.

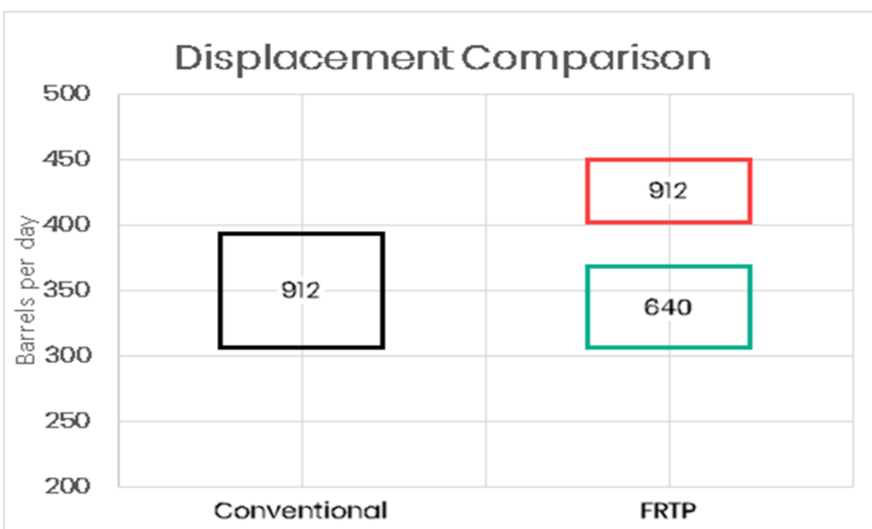


FIGURE 41 – PUMP JACK PUMP DISPLACEMENT COMPARISON

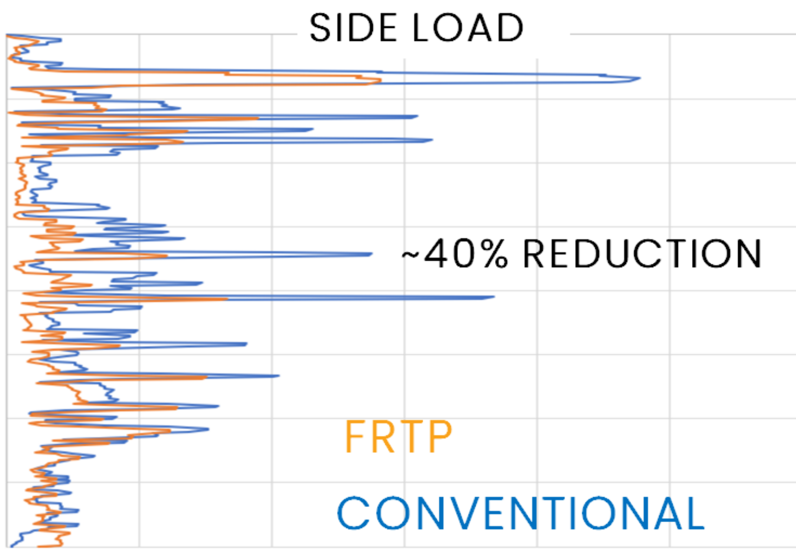


FIGURE 42 – FRTP SUCKER RODS REDUCE SIDE LOADING BY 40% VERSUS STEEL SUCKER RODS

FIGURE 43 – SUCCESSFUL FRTP PONY SUCKER ROD PERMIAN WELL TRIAL

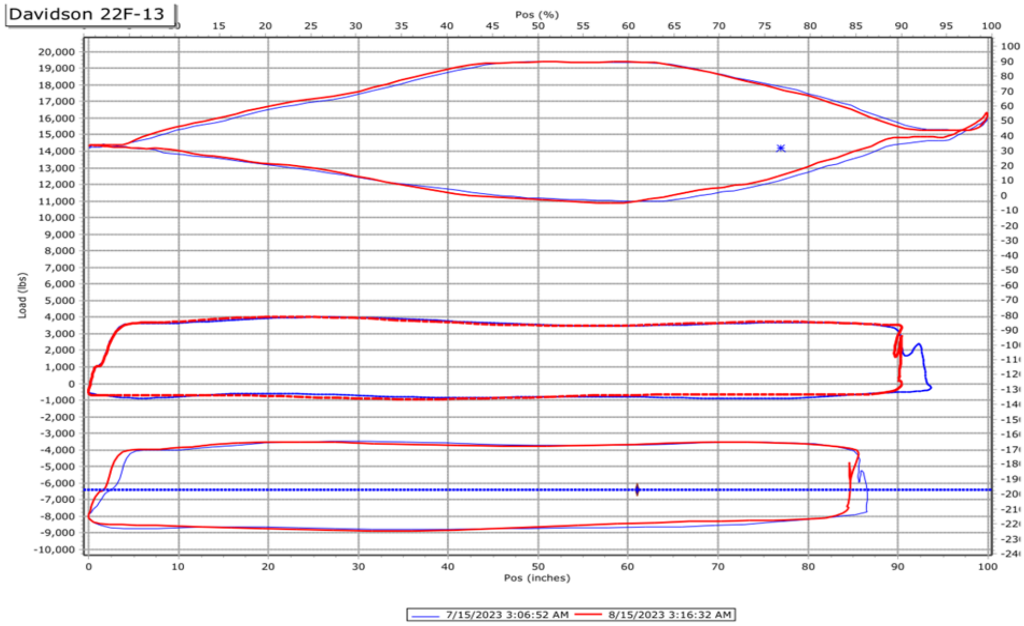


FIGURE 44 – DOWNHOLE PUMP CARDS OVERLAYED THE STEEL RODS

ENDNOTES

[i] S&P Global Rating, 2019, ESG Industry Report Card: Metals And Mining https://www.spglobal.com/_assets/documents/ratings/esg-evaluations/ratingsdirect_esgindustryreportcardmetalsandmining_41672607_jun-05-2019.pdf

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[x] https://www.thoughtco.com/thermoplastic-vs-thermoset-resins-820405, accessed March 11, 2023.

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