MODULUS OF ELASTICITY AND FATIGUE LIFE CONSIDERATIONS IN THE DESIGN AND USE OF FIBERGLASS SUCKER RODS

D. F. Hallden
LTV Energy Products - DuraTech Div.

ABSTRACT

Fiberglass sucker rods have proven to be an economical solution to many sucker rod beam pumping problems. Two important parameters that contribute to the effectiveness of FRP sucker rods are effective modulus of elasticity and fatigue life. Using established computer predictive techniques, it has been shown that FRP sucker rod installations can benefit from using rod designs with a lower modulus of elasticity.

Fatigue life of sucker rods is an important consideration for any sucker rod pumped oil well, for both steel and fiberglass rods. Fatigue life predicitons for steel sucker rods can be routinely determined from API publications and recommendations. Fiberglass sucker rod fatigue life predictions are determined from guidelines supplied by FRP sucker rod manufacturers.

The fatigue life of fiberglass sucker rods cannot be reliably predicted using methods developed for predicting steel sucker rod fatigue life due to the difference in fatigue behavior of the two materials. Therefore, test programs have been developed to generate reliable fatigue life guidelines for field applications.

INTRODUCTION

The modulus of elasticity of fiberglass sucker rods is a significant factor in the successful design and performance of fiberglass sucker rod pumping systems. When fiberglass sucker rods were first introduced, there were many system performance problems. Many of these performance problems could be traced back to the method of predicting fiberglass sucker rod performance. Initially, predictive techniques did not handle modulus of elasticity data properly and in some cases it was ignored. Predictive techniques that are currently used for fiberglass sucker rod design generally require the measured (effective) modulus of elasticity for the fiberglass sucker rods with end connectors and couplings. This value is required to compute the dynamic response of the fiberglass/steel sucker rod system.

Fiberglass sucker rod fatigue life considerations were originally modeled after the steel sucker rod. Premature FRP failures in the field generated new approaches to predicting fiberglass sucker rod fatigue life. Methods of FRP fatigue life prediction that are currently in use have good reliability. These current methods are based on field data in some cases and on laboratory data in other cases.

RELATIONSHIP BETWEEN MODULUS OF ELASTICITY AND SUCKER ROD PUMP SYSTEM PERFORMANCE

It has been difficult to predict the operating characteristics of sucker rod pumping systems due to the nature of the equations of motion that describe these systems. Two approaches have been taken to solve the sucker rod pumping problem.

One is empirical in nature. An analog computer was programmed to generate well operating data. The data was then reorganized into several non-dimensional parameters and presented in a graphical format. A series of calculations using values obtained from these graphs provides a reasonable prediction of well operating characteristics. However, this method will only work for steel sucker rods since the graphs for obtaining the non-dimensional variables were generated for steel sucker rod strings. It is not known how the shapes of these graphs would be altered by using combination FRP and steel sucker rod strings. Attempts to use these graphs with modifications for fiberglass sucker rods have generally met with failure due to inaccuracies in the predictions.

The other method is the solution of a mathematical model of the complete pumping system. The difficulty in this approach is that the equations describing the system have no exact solution and must be solved by numerical methods. The basis of this method is the solution of the wave equation. The wave equation is a partial differential equation as follows:

$$\frac{\partial^2 u}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 u}{\partial t^2} + A + \ldots\ldots\ldots$$

where u is a function of displacement and time, and c is the velocity of propagation of the stress wave in the rod. Additional terms may be added to account for viscous damping, coulomb forces and hysteresis loss, but generally only the viscous damping term (A) is of any consequence. Computer techniques have been in use for many years that will provide a numerical solution to equations modeling pumping systems.

Of these two methods, only the wave equation directly considers the modulus of elasticity as a variable which will affect the dynamic response of the system. The semi-empirical graphical method assumes that the sucker rod material is steel and therefore the modulus of elasticity is treated as a constant (i.e. the method is suitable only for steel sucker rods). In the wave equation, it can be seen that the modulus of elasticity has some effect on the system since the velocity of propagation of the stress wave is

$$c = \sqrt{Eg/\rho}$$

Where: E = Modulus of Elasticity
g = Gravitational Constant
ρ = Density of Rod Material

As the modulus of elasticity increases, so does the velocity of the stress wave.

It should be noted that the velocity equation was derived assuming a homogeneous material. Fiberglass sucker rods are not in this classification. The orthotropic fiberglass rod body velocity formula would probably require some modification. The fiberglass velocity relationship has been approximated closely enough in the current computer predictive techniques so that by entering the actual effective modulus of elasticity, a close approximation to the operating characteristics of a fiberglass sucker rod pumping system can be computed. This was not always true. One predictive computer program required that a specific given value be entered for fiberglass modulus of elasticity. The specific value was about 20% higher than the highest measured modulus of any fiberglass sucker rod. This problem has been corrected.

By using predictive techniques that handle modulus of elasticity data properly, significant differences in pumping system designs using sucker rods with different elasticity can be determined. An example prediction will be used to illustrate the effect of altering the modulus of elasticity of sucker rod material. Table 1 lists the significant operating characteristics of a well with the pump set at 9000 ft. The well is near pumped off and is capable of producing 330 BPD of liquid. The advantages of pumping a well of this type with fiberglass sucker rods are well documented. A typical API design would require a gearbox that would handle a peak torque in excess of 800,000 in.-lb. using API Gr. D rods that are very close to 100% of their allowable load rating. Table 1 was computed using a conventional geometry C456-304-144 surface pumping unit. The advantages of the FRP system can be seen in the lower gearbox loading and lower rod loading. This table also shows that the difference in modulus of elasticity from 6.3×10^6 psi to 7.5×10^6 psi requires different rod string design to produce the same operating characteristics. It has been found that when stroke at the pump is greater than the surface stroke (due to overtravel) the system performance can be improved by the use of fiberglass sucker rods with a lower modulus of elasticity. This improved performance is most evident at shallow to moderate pumping depths and when there is a high pump intake pressure.

The effect of the modulus of elasticity on fiberglass sucker rod string performance is due to the relationship of the velocity of stress wave propagation to the modulus of elasticity. By proper system design, the fiberglass sucker rod strings can outperform steel sucker rod designs. Modulus of elasticity is an important factor in fiberglass rod system design optimization. In short stroke applications the lower fiberglass rod modulus of elasticity performs better with a higher percentage of steel rods. In applications where pump overtravel is generated, the lower modulus of elasticity outperforms the stiffer fiberglass rods.

VARIABLES AFFECTING THE MODULUS OF ELASTICITY OF FRP SUCKER RODS

Of all the factors controlling the modulus of elasticity of a fiberglass sucker rod, the glass to resin ratio is the most important. The higher the glass content, the higher the modulus of elasticity. A second factor affecting elasticity is the fiber itself. Some pumping systems make use of a carbon fiber laminate which has a much higher modulus of elasticity than glass fiber laminates. The resin selection also affects the rods modulus of elasticity but to a very small degree.

FATIGUE LIFE IN FIBERGLASS SUCKER RODS

Sucker rod system performance must include a cost evaluation to determine the true economy of the system. An important item in this cost evaluation is the cost of the rods and how many barrels of oil can be pumped with those rods. The answer to this question is found in the predicted fatigue life of the rod. Longer life can provide a better payback.

There is a great deal of information with respect to the fatigue life of steel. Using this information and field data, API has developed a Modified Goodman Diagram to determine maximum allowable stresses for obtaining satisfactory fatigue life (minimum 10×10^6 cycles). In contrast, the fatigue life behavior of fiberglass rods is not very well documented and reliable field data is difficult to obtain. There is no standardized method for predicting the fatigue life of fiberglass sucker rods. Lack of reliable data and different fatigue life criteria have left some doubt as to how long a fiberglass sucker rod will last in a given application. Yet fiberglass sucker rods are more costly than steel and the fatigue life becomes a significant factor in determining payback periods.

A fiberglass sucker rod system design is optimized when the fiberglass rods are at the "maximum allowable stress." When FRP rods are subjected to lower stresses, they will last longer. (Fig. 1) The fatigue life must be balanced with increased performance for the best economic return. Due to the wide range of economic and operating considerations, no attempt will be made to justify any minimum required FRP fatigue life. However fiberglass rod pumping systems would probably be difficult to cost justify if their fatigue life was less than that of steel rods.

Determination of Fatigue Life in FRP Sucker Rods

Early fiberglass sucker rod installations experienced many premature failures. Many of these failures were caused by improper system design which overloaded the rods. Attempts to analyze FRP sucker rod systems using methods developed for steel rods led to unsatisfactory results. Even if the loading on the fiberglass rods were available, the fatigue life of the FRP rod could not be determined. Allowable stress range diagrams or other fatigue life determination methods were not available.

Steel sucker rod fatigue life behavior cannot be applied to fiberglass sucker rod fatigue life predictions. Steel has a fatigue property called endurance stress (or endurance limit). The endurance stress is that stress at which the number of cycles to failure is infinite. This was originally discovered in stress reversal fatigue tests, but can be also applied to tension/tension cyclic loading. To obtain maximum fatigue life, steel sucker systems are designed to operate below the endurance stress limit for the steel rods. Due to the nature of field applications, the infinite life expectancy is severely reduced to a more realistic value of 10×10^6 (or greater) cycles. Corrosion, rod body surface roughness, wear on tubing, handling, etc. all contribute to this reduction in fatigue life.

For fiberglass rods, there is no endurance stress on which an allowable stress range diagram can be based. This has caused some discrepancies in the way allowable stress ranges are published. Stress range diagrams for fiberglass sucker rods do not indicate the basis for the allowable stresses. It is not possible to predict the fatigue life of the rods from these diagrams. (Fig. 2) Diagrams that do not identify the basis for a valid stress range should be used cautiously. A complete stress range diagram should have several guides to fatigue life, similar to Fig. 3. This allows the system designer to predict the expected life of the rods in the system. Another characteristic associated with fiberglass sucker rods is the inability to predict fatigue properties from ultimate tensile strength (as is done with steel). Fiberglass rods tend to have lower fatigue life when designed for high ultimate tensile strength. Testing techniques such as flex shear, acoustic emissions, ultimate tensile strength, etc. have not proven successful in verifying fatigue life. The only proven method for fatigue life verification is cyclic loading.

Obtaining Data for Predicting Fatigue Life in FRP Sucker Rods

Two sources of data can be used to generate graphs or formulas for predicting fiberglass sucker rod fatigue life. One source comes from field operating data and the other comes from laboratory fatigue testing. Both methods will be reviewed.

Fatigue Life Predictions from Field Operating Data

By obtaining loading data from dynagraph cards (or other field measuring techniques) for a large number of operating stress ranges, the allowable limits for stresses can be roughly determined. This is a difficult method to apply since there is no absolute criteria for judging a successful load range application. Typically a reasonable criteria for a successful system would be based on a minimum number of load cycles before failure (about 10 million in the case of steel sucker rods). Pumping continuously at 10 strokes per minute, it would require almost 2 years to accumulate the data necessary to verify a 10 million cycle fatigue life. It is a very time consuming method. Due to the unknown allowable working stresses, it is probable that some systems will be overstressed. This will cause premature failures and thus incur high costs for obtaining data. Field failures due to unknown fatigue life may also cause problems with respect to product reliability.

In addition to the time and cost aspects, other field variables may affect the fatigue life data. These would include excessive rod body wear due to a deviated hole or dog leg, high temperatures, variation of well operating characteristics with time, fluid pound, etc.

Fatigue Life Predictions from Laboratory Data

Laboratory testing is an excellent means for determining the fatigue life of fiberglass sucker rods in oil well pumping conditions. By testing the rods in a controlled environment, fatigue life in field applications can be predicted by using appropriate service factors.

Laboratory fatigue tests can be conducted with precise control of load level, temperature, cycle rate, and rate of loading. In addition, accurate counts of cycles to failure can be obtained in relatively short time periods. Fatigue failures in the laboratory environment establish the upper limits for system design, thus avoiding the high cost of fatigue failures in the field. Fatigue tests can be accelerated in the laboratory by subjecting the rod samples to higher loads than they would be exposed to in field applications. The cyclic fatigue testing equipment is costly to obtain, but when compared to the cost of field failures, it is the most effective way of obtaining the necessary fatigue life information for successful field applications. Significant parameters that contribute to the fatigue life of fiberglass sucker rods have been discovered in laboratory testing that would probably go unnoticed in field tests.

CONCLUSIONS

The modulus of elasticity of sucker rods is important to the pumping system performance due to its relationship with the velocity of propagation of the stress wave. The lower modulus of elasticity of fiberglass sucker rods contributes to increased system efficiency. Fiberglass sucker rod pumping systems should be designed to make maximum use of their effective modulus of elasticity. The percentage of glass is proportional to the modulus of elasticity.

Sucker rod system designs must rely on fatigue life guidelines to be effective. A standard guideline exists for steel sucker rods based on the endurance stress property of steel. No standard guideline exists for the fatigue life of fiberglass rods. Accurate fatigue life diagrams are required for each type of fiberglass rod manufacture since fatigue life varies with the rod system design which includes the rod stock, end connector design as well as adhesives.

REFERENCES

1. Thomson, William T., Vibration Theory and Applications, Prentice-Hall,Inc., 1965, Page 268.

2. Gibbs, S.G., Predicting the Behavior of a Sucker Rod Pumping Systems,SPE Paper presented at SPE Rocky Mountain Regional Meeting, May 27-28,1963, Denver, Colorado.

Table 1
Operating Characteristics of a 4000 Ft. Well

Approximately 380 BPD (100% Theoretical) Near Pump Off Using C320-213-120 Surface Pumping Unit

FRP Modulus of Elasticity (PSI)	% of Rated Gearbox Ldg.	Pump Dia.	Strokes Per Minute	Theoretical Production	Fluid Level (FT.)	Max. Stress (BPD)	Min. Stress	% Allowable Loading	Stroke @ Pump (IN.)
6.3×10^6	71.8%	1.5"	11.4	409	1200	15,500	3,400	63.8%(1)	134
6.3×10^6	99.9%	1.5"	11.4	385	4000	20,100	3,200	88.8%(1)	127
7.2×10^6	73.6%	1.5"	11.4	399	1200	15,500	3,200	89.4%(2)	131
7.5×10^6	104.6%	1.5"	11.4	377	4000	20,500	2,700	98.9%(2)	124

(1) Based on Fig. 3
(2) Based on Fig. 2

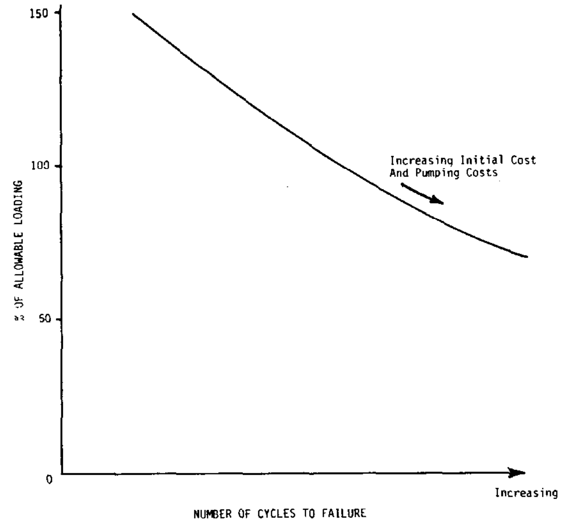

Figure 1 - Fatigue life of FRP sucker rods subjected to tension/tension cyclic loads

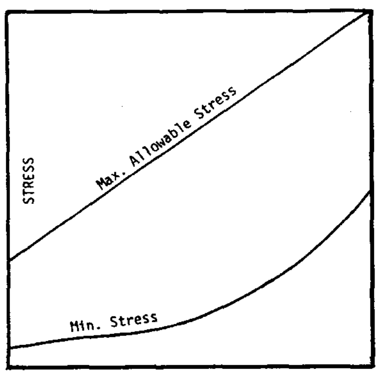

Figure 2 - Stress range diagram

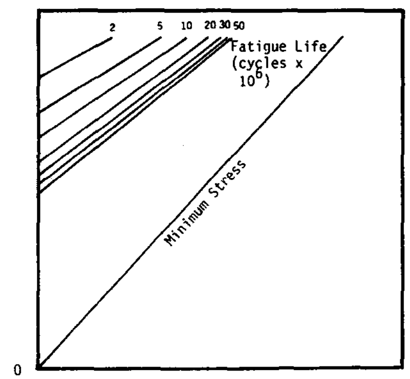

Figure 3 - Fatigue life diagram