Polished Rod Loads and Their Range of Stress

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FATIGUE ENDURANCE LIMIT

Practically all sucker rod breaks are fatigue failures. These breaks are brittle type fractures which occur at a stress much below either the ultimate strength or yield strength of the metal after a great number of stress reversal cycles. This type of failure is common to all metals and all kinds of metallic structures subjected to cyclic loading. To design a structure so that such failures cannot occur, we must determine the fatigue endurance limit of the metal we are using, then limit the working stresses to a safe value below this figure.

The fatigue endurance limit, operating in air for the steels we use in sucker rods, is usually a stress equal to from fifty to sixty per cent of the ultimate strength of that steel. It can be defined as that maximum stress level at which the steel will operate in complete reversals of stress from tension to compression for a minimum of ten million cycles. Any higher stress would result in failure at a lesser number of cycles. One peculiarity of steel is that if it will withstand ten million cycles under any given stress, it will last indefinitely.

The fatigue endurance limit is determined in the laboratory under carefully controlled conditions. Specimens are prepared of proper dimensions, carefully polished longitudinally, and subjected to carefully controlled cyclic stresses (usually as a rotating beam) at various stress levels until the critical level is found. The data is then plotted as an S-N (stress-number of cycles) curve as shown in Fig. 1. Much has been written about this subject[1,2], and further detail is beyond the scope of this paper.

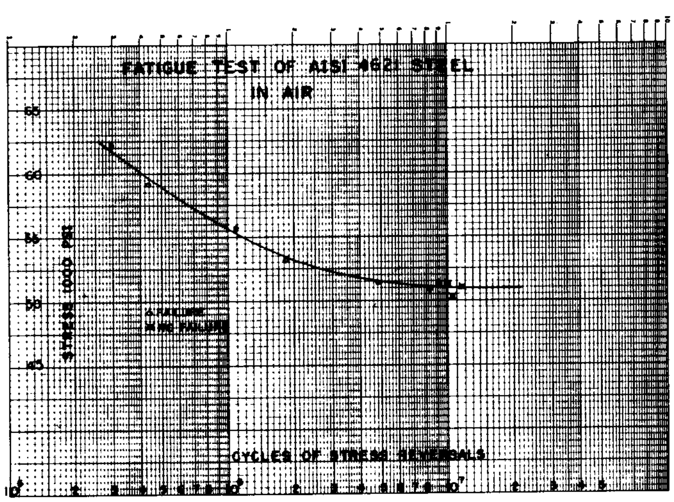

FIG. 1

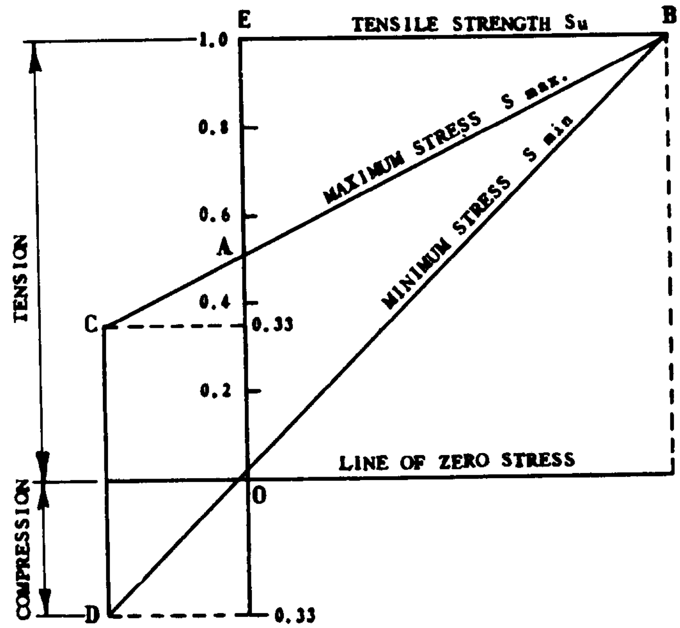

FIG. 2

The fatigue endurance limit, as defined and determined above, is affected by many things. It is materially affected by notches, nicks, corrosion pits, decarburized surface of the steel, inclusions, corrosive environment, and any surface imperfections. It can even be raised by excluding the air.[3] All of these effects must be taken into consideration in determining the safe operating stress.

So far, we have discussed fatigue endurance level as determined by completely reversing the stress from a maximum in tension to the same value in compression. But sucker rods, nominally at least, are not subjected to compression. They are subjected to a pull-pull stress from a maximum in tension to a minimum, still in tension, and back again. This type of loading, too, affects the maximum endurance limit of the steel, and is vital to the proper design of sucker rod strings.

Allowable Stress

The Goodman diagram in Fig. 2[4] shows in a general way how the maximum allowable stress varies with the minimum, or range of stress. It starts at the left of the diagram with a range of stress from a maximum of one-third the tensile strength in tension to a minimum of one third the tensile strength in compression, and increases as we go to the right with an increasing minimum and decreasing range, until the maximum and minimum meet with no allowable range at the tensile strength, Su. It will be noted that as the minimum stress becomes higher, the maximum allowable stress also becomes higher, but the range decreases. Conversely, as the maximum stress becomes lower, the range of stress becomes greater, with a lower minimum stress.

This trend or pattern of allowable stress is not only very applicable, but is of extreme importance to the proper design and economical life of sucker rods. When operating under high stress levels, our range of stress must be kept small by maintaining a fairly high minimum stress. Fortunately, this situation usually exists in deep wells where the weight of the rods is high compared to the weight of the oil being lifted. However, in medium depth wells with large plungers and high speeds, the down stroke load or minimum stress is quite apt to be low, so the maximum stress must be limited to accommodate the larger range of stress. We, therefore, need a modified Goodman diagram for the proper design of such strings. Many such modified Goodman diagrams have been devised.

For our purposes then, considering 4621 steel for non-corrosive service, we start with a modified diagram as shown in Fig. 3. We will consider corrosive service later. First of all, we feel that our diagram should have its lines converging on the yield strength at "A" rather than the tensile strength of the steel, since stressing beyond the yield point changes the physical properties of the metal. Second, since we know that operating sucker rods in compression generates large, unpredictable and disastrous stresses, we will start the minimum stress line at zero. Finally, we have arbitrarily set the maximum stress point, corresponding to a zero minimum shown at "B", at one half of the laboratory determined air fatigue endurance limit of the alloy in question, in this case 4621 steel.

Actually, this gives us a four to one safety factor over the fatigue endurance limit as determined with the rotating beam specimen. It eliminates all of the compression stress, which makes up half of the actual range of stress to which the laboratory specimen was subjected, and uses only half of the remainder. A four to one safety factor is none too large, considering all of the variables under which a sucker rod operates. There is the hot rolled surface of the actual rod with its inherent imperfections to consider, compared with the machined and polished surface of the laboratory prepared specimen.

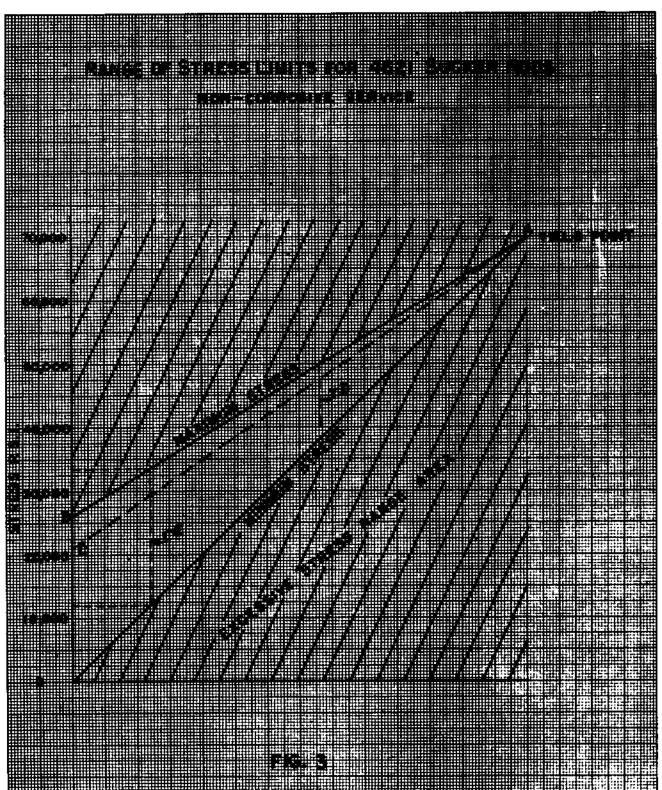

FIG. 3

One check on the validity of the resulting diagram is the stress level and range of stress to which the pins are subjected when properly tightened and subjected to high working loads. It has been shown that a 7/8 inch pin tightened to a stress of 40,000 psi with the string cyclicly subjected to a 20,000 pound load, will alternately be stressed between the 40,000 psi and about 50,000 psi. This range of stress is shown on the diagram at "D" and is seen to fall within the allowable range. A great many pins have been tightened to this recommendation, and it has been field proved that pin breakage has been thereby eliminated.

We would never think of operating AISI 4621 steel rods at 50,000 psi maximum stress; but, in the joints, where the range of stress can be effectively limited to a low figure, it is being done every day--and that in spite of the severe notch effect of the threads! During the past year, the allowable stress levels and ranges, as illustrated by this diagram, have been checked against many well string designs and have, in all cases, appeared to be valid. It imposes no lower polished rod loads than have been customary in the past in most cases, and has helped explain why strings with a high range of stress have failed.

Maximum And Minimum Stress

To apply this principle and the diagram to the design or analysis of actual strings, we need to know both the maximum and the down stroke or minimum stress. Of course, the ideal means of determining both is through the use of dynamometer cards. Too often, and in particular in designing new strings, such cards are not available, so we must have a means of estimating them. The maximum stress can be determined by calculating the maximum load, using customary formulae such as the Mills, Slonneger, or other formulae, and dividing by the rod area. The Mills and Slonneger formulae are:

$$PRL = W_o + W_r \left(1 + \frac{LN^2}{70,500}\right) \qquad \text{- Mills}$$

$$PRL = (W_o + W_r)\left(1 + \frac{LN}{5400}\right) \qquad \text{- Slonneger}$$

where: PRL = Polished rod load in pounds
W_o = Weight of oil in pounds
W_r = Weight of rods in pounds
L = Length of stroke in inches
N = Number of strokes per minute

The minimum or down stroke load is usually considered equal to the weight of the rods decreased by the acceleration factor minus the buoyancy of the rods in the fluid. Buoyancy in this case cannot be neglected as is customary in calculating maximum load, for buoyancy and friction both work in the same direction on the down stroke, thus reducing it. The following

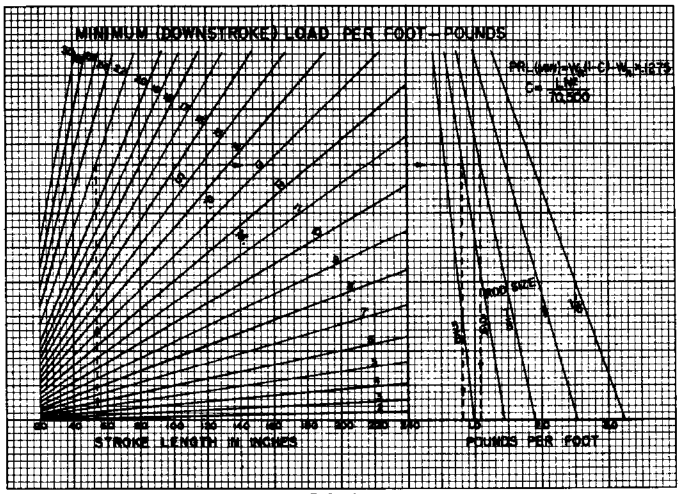

FIG. 4

formula expresses the minimum load:

$$PRL\ (Min) = W_r \left(1 - \frac{LN^2}{70{,}500}\right) - W_r \frac{62.5}{490}$$

This load can be read directly from Fig. 4. The value obtained from Fig. 4 is then multiplied by the depth and divided by the rod area to obtain minimum stress. Incidentally, the approximate stress per foot can be read directly by using the curve for 1-1/8 inch rods. This is true because the area of a 1-1/8 inch rod is approximately one square inch, and density of 25-foot rods with upsets and couplings per foot is approximately the same for the several sizes. Fig. 5 gives the minimum stress directly, in terms of the acceleration factor, $\frac{LN^2}{70{,}500}$. An example will help to clarify the use of these diagrams.

Depth 3300 feet 3/4 inch type 4621 rods
Strokes per minute 22 Pump size - 2-1/4 inch
Stroke length 54 inches

Polished rod load $= 3.142 \times 1.426 \times 3300$
$= 14{,}786$ pounds

Maximum stress $= \frac{14{,}786}{.442}$ 33,525 PSI

Min. allowable stress from Fig. 3 = 12,000 PSI ("E")
Min. load per foot from Fig. 4 = .81 pounds per foot
Min. stress $= \frac{.81 \times 3300}{.442} = 6{,}048$ PSI

Since 12,000 psi is the minimum allowable stress from Fig. 3, the range of stress is too large. We should try a tapered string of 7/8 inch and 3/4 inch rods.

Polished rod load $= 3.350 \times 1.426 \times 3300$
$= 15{,}764$ pounds

Maximum stress $= \frac{15{,}764}{.601} = 26{,}200$ PSI

Minimum allowable stress from Fig. 3 = 350 PSI

Referring again to Fig. 4 for the 3/4 inch and 7/8 inch rods, the minimum load per foot for each size is .81 pounds and 1.09 pounds respectively, which when multiplied by the length of each section and divided by the area of the 7/8 inch rod, will give 5,121 psi, well above the minimum allowable stress of 350 psi. The 7/8 inch and 3/4 inch tapered string would be satisfactory.

Under corrosive conditions, if one hundred per cent effective inhibitors are applied, the stress limits shown in Fig. 3 graph for noncorrosive service may be used; if inhibitors are not one hundred per cent effective, the maximum allowable stress limit must be reduced to the following percentages of maximum:

TABLE I

Rod Grade	1036	8627	4621	High Tensile
Salt Water	63%	75%	80%	85%
Hydrogen Sulphide	---	53%	64%	65%

For example: If the minimum stress for a string of 4621 rods is 14,000 psi, the maximum for salt water operation would be:

35,000 x .80 = 28,000 PSI

and for hydrogen sulphide operation, would be:

35,000 x .64 = 22,400 PSI

It should be remembered that all well fluids are

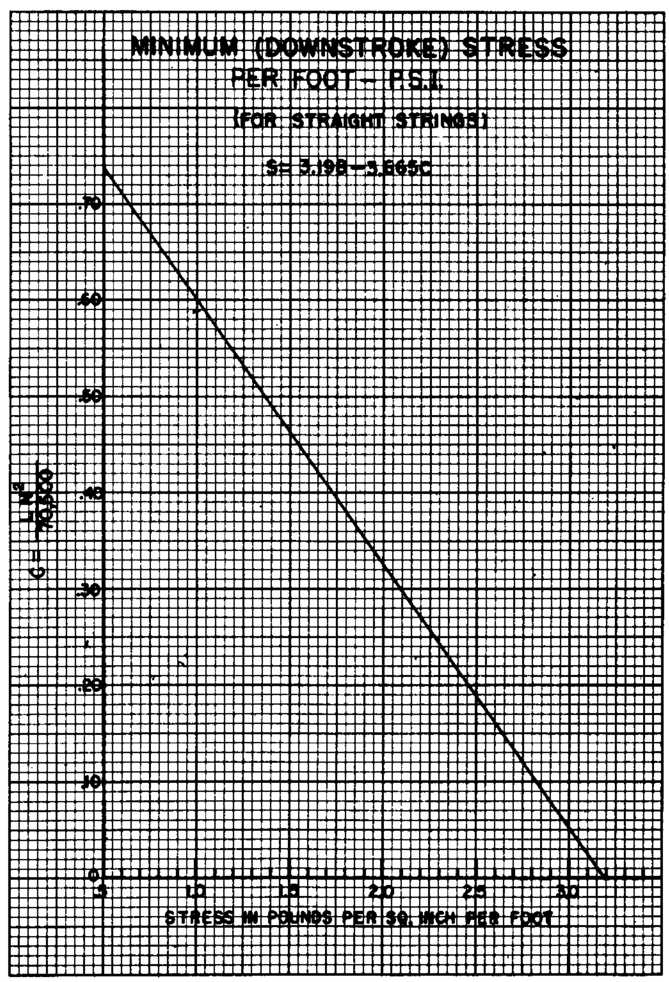

FIG. 5

corrosive to some degree. The above figures represent our experience under average conditions. Where corrosion is above average, these figures must be further reduced. Experience in the particular pool under consideration is the only positive criterion. The use of an effective inhibitor will usually prove to be economical.

Separate Graphs

Separate graphs can be made for each of the conditions shown in Table I, or lines can be dotted in for these several cases as shown in Fig. 3 at "C" for salt water operation. Actually, the location of point "C" can be chosen by experience gained in the particular field under consideration. For instance, actual experience in an area that is only mildly corrosive might indicate that point "C" for salt water operation of 4621 steel, shown in the table as 80% of 52,000 psi or 20,800 psi, might be safely raised to, say, 22,000 psi. Conversely, it might be necessary to lower it.

Of course, separate graphs should be made for each of the different alloys used for sucker rods, as point "B" will vary with each, depending on the fatigue endurance limit of the material in question. The high tensile sucker rod steels, for instance, will have an endurance limit of around 70,000 psi; hence, point "B" for these rods will be located around 35,000 psi.

For convenience, graphs can also be made to read load in pounds directly if separate graphs are prepared for each size rod. With five sizes and as many alloys, however, we would then have twenty-five graphs, which would be quite voluminous.

It has been customary in the past for most sucker rod manufacturers to recommend maximum polished rod loads for the various size rods under various types of corrosive services. Some of them, however, have qualified these recommendations by further limiting the range of stress to a certain percentage of the maximum stress. Since range of stress has been recognized for some time as being extremely significant, and since the trend of its effect is known to be illustrated by the Goodman diagram shown in Fig. 2, the methods outlined in this paper for taking it into account become valid and convenient. A flat figure for maximum load or stress with no consideration for range of stress can very well get the sucker rod string designer in trouble. By employing graphs similar to the one shown in Fig. 3, a more logical and far safer design will result.

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