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Designing for Reinforcement Load Sharing

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Abstract
Hose design has been neglected as an engineering topic. Hose Technology, 2nd ed., Colin W. Evans, applied science publishers, Essex, England, 1979; has been cited as a design resource. Paper 1 makes a correction to the Evan's design equation; and this paper extends the solution to indicate how to distribute equally those design loads throughout the reinforcement. **Introduction:** This paper documents how to resolve the tensile requirement for the reinforcement based on how many reinforcement ligaments are required to support those forces. **Method/Approach:** The article looks to the tensile test results for the selected reinforcement ligament and illustrates how the elongation of the reinforcement as related to the manufactured length of the reinforcement are related so that the pressure loads are equally shared. **Conclusion:** The paper concludes all of the reinforcements must be the same manufactured length for the hose reinforcement to uniformly distribute the reinforcement tension. All strand lengths in a multilayer hose must be the same length for proper load sharing.

Key words: Hose reinforcement load sharing; Reinforcement strand tensile test

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INTRODUCTION

The article "IS HYDRAULIC HOSE TOO STRONG?" presented an alternate concept for designing reinforce for hose constructions. The key idea from the article is:

Reinforcement Design Statement	
R x N **= P x 1.36 x** $\mathbf{D_n^2}$**;** with the reinforcement's **pitch angle applied at** $\mathbf{54^0}$ **44'**	
R x N	Defines the minimum design requirement for the reinforcement construction. N is empirically determined to provide sufficient tube coverage to prevent tube wall failure.
R	The minimum tensile strength of the wire or yarn ligament; and it is a vector quantity since it has a direction; and is operates in parallel and opposite to the hydrostatic forces in the hose assembly. **R** is assumed to be the same among all strand lengths, N.
N	The minimum number of reinforcements ends necessary to provide both coverage and strength to reinforce the tube.
P	The **Design Pressure** for the construction. In general, the design pressure divided by the engineering safety factor is defined as the **Operational Pressure**.
D_n	Is equal to the fitting nipple's diameter and is the critical reinforcement design dimension.
$\mathbf{54^0}$ 44'	Defines the neutral pitch angle and forms naturally when the internal hydrostatic forces in the axial and radial directions are equal.

Reinforcement Design Statement is similar to what Colin Evans presented in his volume of Hose Technology. What is the difference? The Evans approach uses the mean braid diameter of the reinforcement as the critical design criterion while the proposed analysis recommends the nipple diameter as the critical design criteria.

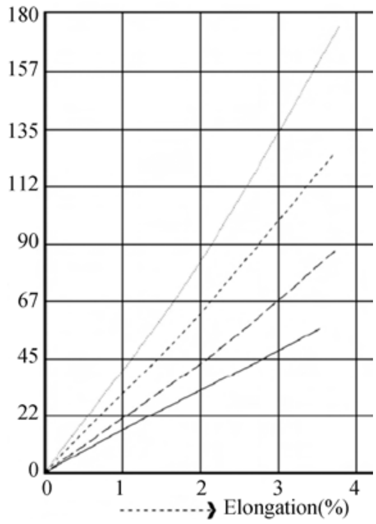
This article presents another idea regarding hose reinforcement mechanics. What is the proposal? Hose reinforcement constructions consist of a symmetrically arranged assembly of individual wire or yarn ligaments. These ligaments must work together to cover the tube to resist the hydrostatic forces generated at the fitting nipple and tube wall. The ideal arrangement of ligaments shares those forces equally; this is an assumption used by the **R** x N requirement.

One consequence of Reinforcement Design Statement, the expression **R** x N, requires the load to be evenly shared. The goal of this article is: Designing for reinforcement load sharing.

1. ALL WIRE AND YARN REINFORCEMENT IS ELASTIC

Think of each hose reinforcement strand as a spring. Each strand of wire or yarn has a "force versus elongation" tensile test result similar to that shown in **Figure 1.**

Reinforcement yarn tensile test results demonstrating elasticity $R = K \times \Delta L$ For Yarn, $K = M/L_0$ and for Wire, $K = EA/L_0$



The graphs to the left are summary tensile test results[1] for 3000, 2250, 1500 and 1000 denier para-aramid yarns.

The recorded breaking strength[2], **R**, of the 1500 denier yarn is around 87 pounds measures an elongation of 3.7%.

The estimated spring rate for the 1500 denier yarn is:

K =D**R**/ΔL = 87#/.37" = 235 pounds/inch for a 10" gage length yarn. The spring rate, EA/L_0, will change as the yarn's gage length[3] "L_0" increases or decreases.

Figure 1
Reinforcement Yarn Tensile Test Results Demonstrating Elasticity

This graph illustrates when a pull applied to the yarn (or wire) strand, it lengthens by some proportion. It shows Tension, **R** causes an elongation percentage equal to $\Delta L/L_0$. This is what a spring does. Think of hose reinforcement as a set of parallel springs, symmetrically arranged to cover the tube.

2. LOAD SHARING WITHIN A REINFORCEMENT CONSTRUCTION

Figure 1 illustrates the spring rates for four para-aramid yarns and is taken directly from the manufacturer's technical data set. Metallic wire manufacturers provide similar tensile test data in their technical literature or quality control documents. The spring rate provides important design information for the creation of a reliable reinforcement construction.

Let us consider reinforcement wire; it is selected to keep the development simple. Yarn reinforced hose assemblies use the same design tools.

A wire tensile test produces a straight line curve in the elastic region similar to that shown in Figure 1. We have a relationship between tensile force, **R**, and elongation $\Delta L/L_0$. Each tensile test for metals provides data in the form of: Stress/Strain is equal to the Modulus of Elasticity (E.)

Or in symbolic form: $(\mathbf{R}/A)/(\Delta L/L_0) = E$ where A is the cross sectional area of the test article; ΔL is the measured elongation and L_0 is the original or gage length of the test article.

Wire, and similarly yarn, has a spring rate that is determined by the tensile test data. Since a spring rate

[1] Results are for Teijin Twaron 2300 series para-aramid yarns found in their advertised (open source) technical data. "R" is selected to avoid confusion. Ordinarily, tension is represented by "T or F."
[2] "R" is selected to avoid confusion. The source is the Evans' paper. Ordinarily, tension is represented by "T" or "F."
[3] A typical gage length (L0) for yarn tensile testing is 10" because the measured elongation is easily converted into a percentage figure.

is given by $\mathbf{R}/\Delta L = K$; then K for a wire is EA/L_0; and similarly, for yarn[4] is $\mathbf{R} = Y/L_0 \times \Delta L$.

The spring rate is sensitive to the ligament length, L_0 because the other variables like the wire material's modulus of elasticity and the wire's cross sectional area fixed. So the only engineering and manufacturing variable for reinforcement is the ligament length, L_0.

So the ligament length (L_0) impacts the spring rate; and the longer the ligament, the softer the spring; and visa-versa. So, for equal load sharing, the spring rate among all of the parallel springs must be the same and since, $\mathbf{R} = EA/L_0 \times \Delta L$; and since the strength of the reinforcement is the sum of the strengths of each spring, therefore, the ligament length (L_0) is the critical factor for equal load sharing in a hose reinforcement construction.

3. SINGLE LAYER REINFORCEMENT DESIGN FOR LOW AND MEDIUM PRESSURE HOSE ASSEMBLIES

For low and medium pressure hose constructions using a single reinforcement layer; it is straight forward to keep the reinforcement lengths in the construction the same. The standard practice is to apply the braided reinforcement at the neutral angle. Wire reinforced hose assemblies "naturally" form with equal reinforcement lengths as long as good manufacturing practices are employed. Single layer yarn constructions are more difficult to make because the strands are noodle like.

4. MULTIPLE LAYER REINFORCEMENT DESIGN FOR HIGH PRESSURE HOSE ASSEMBLIES

As indicated by the Reinforcement Design Statement, we need to formulate "**R** x N" for the production of a successful hose assembly. For a single layer reinforcement design, the coverage "N" dominates the design and must provide sufficient tube coverage. We can choose any wire or yarn so that the tensile strength, **R is greater than** $\mathbf{(P \times 1.36 \times D_n^2)/N}$**.** If our preliminary work determines we cannot find such a material, then we will have to resort to a multiple layer construction.

5. THE OPPOSING BRAID ANGLE LAYER DESIGN APPROACH

One multi-layer hose reinforcement design practice for high pressure hose assemblies recommends the reinforcement should be staggered . The idea assumes the inside reinforcement layer (say at 53^0) "swells" up to meet the upper reinforcement layer (say at 56^0) while the upper reinforcement layer lengthens and compresses upon the inside reinforcement layer. Let us look at the details.

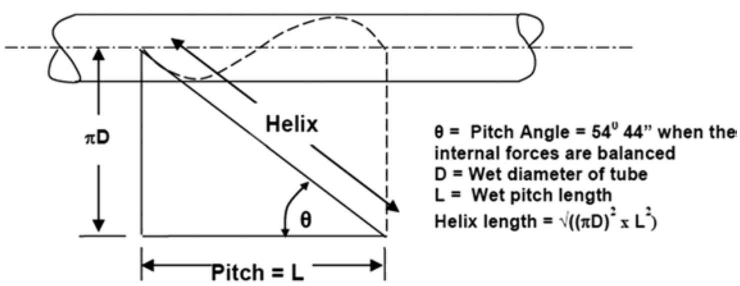


Figure 2
Illustration Showing One Reinforcement Strand as It Is Unwound From the Construction

Figure 2 illustrates a reinforcement strand unwound from the helix of one layer. This is representative geometry. It shows the length of the ligament (L_0) is related to the pitch angle (θ). All of the trigonometric relationships apply.

It is proposed equal load sharing requires equal reinforcement wire or yarn length, L_0. A single layer reinforcement construction finds the neutral angle because the internal forces drive the strands there. Do the same rules apply to multiple layer reinforced hose assemblies?

Figure 3 illustrates why the design strategy that applies hose reinforcement at unequal braid angles fails. First of all, the ligament lengths of the reinforcement installed at 53^0 are shorter than the strand lengths of the reinforcement installed at 56^0. Based on our spring rate arguments, the 56^0 ligaments will have a smaller tension than the 53^0 strands. So the inside layer at 53^0 will carry more hydrostatic pressure load than the ligaments in the outside layer.

Do the inside strands "swell" up while the outer ligaments "compress"? Consider high tensile braid wires have a measured elongation of about 1-1/2% and yarns have a measured elongation of around 4-1/2% until they break. Secondly, the ligaments in the upper layer do not "shrink" to meet the length of the ligaments in the lower layer. Lastly, the length ratio between the upper and lower ligaments is: 17.88"/16.62" = 1.076. The percentage length difference of 7.5% and is greater than the allowable elongation to breakage for either wire or yarn.

[4] Yarn's spring rate is involves concepts such as Denier and Modulus and is simply presented as Y/L0.

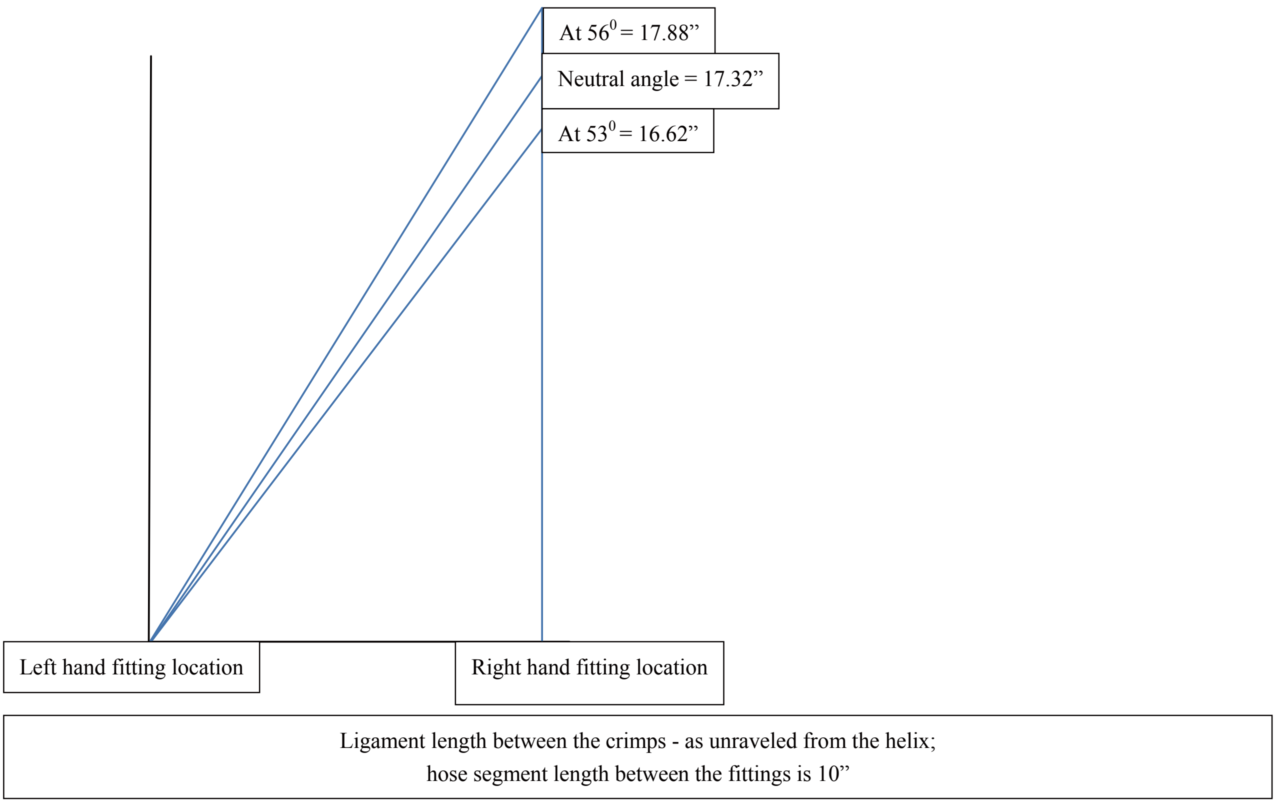


Figure 3
Illustrates the Relative Lengths of Unwound Strands From a Hose Construction Using a Contemporary Design Idea

Consider the inner layer strands move until it is equal to the neutral angle and the inner ligaments will elongate some ΔL to meet the hydraulic forces and they may break if the elastic limit is exceeded. Do the ligaments in the outer layer elongate to carry any load?

As the inner braid responds to the hydrostatic forces, the braid angle is compelled to move towards the neutral angle; and the hose assembly shortens from 10” to around 9.83”. It will not be exactly that because the ligament will lengthen by some amount in response to the hydrostatic pressure forces. What happens at the outer braid?

Remember the outer ligament length is 17.88” and the distance between the fittings has shortened by some length as the reinforcement on the inside layer moves to the neutral angle. The resulting braid angle for the outer braid may more to around 56.6^0. The braid angle for the upper layer is relaxing – and in the absence of other forces such as friction – it is not doing any load sharing. Strand load sharing occurs only if the strand lengths in both layers are the same.

6. OPTIMUM SOLUTION FOR MULTI-LAYERED REINFORCEMENT

Hose reinforcement is the physical manifestation of a vector. Under pressure all reinforcement ligaments impart a tension (**R**) at the neutral angle. All of the ligaments are springs that elongate in proportion to the hydrostatic pressure created force. “Load sharing” is achieved by making all of the ligament lengths the same so the strain among all of the ligaments is the same.

Figure 3 graphs the relationship between ligament length and braid angle as applied over a 10” length; where each ligament length applied at the neutral angle is about 17.32”. The ligament length must stay the same regardless of layer location within a multilayer reinforcement construction. It is the ligament length that governs load sharing. All of the strands must be installed at the same angle between the fittings to be the same length. Then all of the “spring constants” for all of the ligaments are the same and therefor elongate the same amount when under hydraulic pressure. Then we have equal load sharing. So the critical measure is the ligament length (L_0) as controlled by the manufacturing process.

7. SUMMARY OF SOME IMPORTANT IDEAS REGARDING HOSE REINFORCEMENT MECHANICS

Reinforcement Design Statement 1	**R** x N **= P x 1.36 x D_n;** The nipple diameter is the critical design criteria.
Neutral braid angle	Keeping the construction ligaments at the 54^0 44' braid angle is critical.
Reinforcement spring constant	**R** = K/L_0 x ΔL and indicates reason why equal ligament length is important.
Load Sharing	The reinforcement's strength is equal to the sum of the strength of each ligament and load sharing is accomplished by keeping all of the ligament lengths (L_0) the same. This is a critical requirement.

Aside: This analysis is suitable for both braided and spiral hose reinforcement constructions. Note a hose strand that is braided has increased stress levels because of the work hardening imparted by the braid geometry.

REFERENCE

Wire Angle Response Characteristics in Hydraulic Hose. (n.d.). SAE Paper 972706

