REFINING OUR RULES OF THUMB

By

Ronald Lynch
RJLynch & Associates, LLC
USA

ABSTRACT

Rules of thumb are common in web handling for good reasons. Many of the theories of web behavior are still under investigation and often are complex and a function of properties that are difficult to measure. Because of this, we rely on simple rules of thumb to estimate what are acceptable tensions in a web path. To be safe, these rules of thumb are often very conservative. As we push webs to run faster and more efficiently, we need to refine these rules to meet the new challenges. I wouldn't want to fly in an airplane that was designed with rules of thumb developed years ago for other materials, and I wouldn't want a converting line designed the same way. This paper goes beyond rules of thumb and presents several factors that can help us understand what tensions are right for our webs. It also identifies some area where the knowledge gaps still need to be filled.

NOMENCLATURE

A	Linear Acceleration, m/sec^2
B	Basis Weight kg/m^2
D	Idler Drag, N
g	Acceleration of gravity, 9.8 m/sec^2
L	Span length, m
M	Mass, kg
R	Radius, m
S	Web sag in a span, m
T	Tension, N
W	Width, m
μ	Coefficient of friction
θ	Wrap angle, radians

Subscripts

h	high
l	low

INTRODUCTION

When I first started in web handling in the 70's, in toilet tissue converting, tension was an abstract concept. It was controlled by a dancer, but was never specified, measured or quantified. It was left to the operator to feel the web and decide to turn the knob this way or that based on preference and experience. In the 80's, I learned some of tension's folklore, e.g., too much causes this, too little causes that, etc. These were useful troubleshooting tips, but not a foundation for engineering new equipment. When I started teaching web handling to new hire engineers in the 90's, I needed something better to tell students. I developed this framework of formulas and measurements for designing new equipment to run new webs. The framework still incorporates some estimates and rules of thumb, but it is a framework to build on and is better than what I started with.

TENSION AND STRAIN ARE NOT THE SAME THING

Tension is a force and determines how the web interacts with the things it touches, i.e., rollers, air, other webs, and gravity. Strain is about dimensions and dimensional changes. It is more about what is happening to the web and inside the web. Tension in this paper is in force units, lb or N, but the concepts and formulas can be adjusted for material stress, N/m, or classic engineering stress, N/m^2. Strain is classic engineering strain, the change in length divided by the original length. Tension and strain are related by modulus, but it is helpful to think of them independently and develop separate criteria.

THERE ARE LIMITS

First, we can imagine that there are maximum and minimum failure limits for tension and strain. These are limits that we cannot, or do not, want to cross because bad things happen: the web breaks, the machine breaks, or quality is so bad that we would not continue to make the product. If we can identify these limits, we can pick the most constraining upper and lower limit and set them as our failure limits.

One upper strain failure limit is damage to the web. What we call damage depends very much on the web and the intended use for the web. It is up to the product developers to define the limits of strain that can be tolerated. Damage can start to occur at a strain lower than the breaking strain. Strain in the elastic range is usually not causing damage, but where permanent deformation starts, the fibers or molecules of the web are being broken and rearranged, and we are starting to alter the properties of the web. The onset of permanent deformation or property changes can be used to define an upper limit for strain. In some cases permanent deformation is unavoidable, or intentional, and a target for the amount of permanent deformation strain defines the limit, beyond the limit, bad things happen. Notch sensitive or brittle webs may not show damage or permanent deformation, but rather, they just break. These webs may require a very low upper strain limit to avoid sudden failure. The types of things to look for in any web are loss of strength of the web, curling of laminates where one ply is permanently deformed, but not the others, or a permanent change in web width. Webs can deform viscoelasticly even at low strain. Recovery of viscoelastic strain in the final product can result in dimension change of the product. Since viscoelastic strain can occur in the parent roll, limits for strain sometimes need to be applied to making and converting process through the entire supply chain.

An upper failure limit for tension is damage to the equipment. Most machines are, or should be, designed to a specified loading condition. Rollers and frames are sized based on the expected web tensions. If we define equipment damage as deflection of rollers to the point of causing tracking and wrinkle problems, we can define an upper limit for tension. In the popular literature there tables of acceptable dimensional tolerances for roller deflection and misalignment. Using the tolerances and equipment drawings, upper limits for tension and loading can be defined for a given machine. For new work, the rollers and frame should be engineered to support the expected tension while maintaining adequate alignment. There is a penalty for oversizing equipment to support high tension. It requires heavier frames and larger diameter rollers which increase roller inertia and bearing drag, raising the minimum tension demands on the web. It also increases cost.

One low tension failure limit is the minimum tension required to maintain traction with idlers. The force to drive an idler is transmitted to the idler's surface by friction with the web. The amount of friction force available is a function of web tension, the coefficient of friction, μ, and the wrap angle. The amount of force demanded by an idler is a function of velocity, acceleration, bearing drag and inertia. The highest demand is near the end of acceleration when the velocity and bearing drag are highest and the inertial load is still present. We can define idler drag as the force required at the surface of an idler needed to keep it spinning at a given velocity and acceleration. This force comes out of web tension and creates a tension difference across the idler

$$\Delta T = Drag \qquad \{1\}$$

Assuming a hollow shell idler, we can calculate the force required at the surface of the idler needed to accelerate the idler as

$$F = MA \qquad \{2\}$$

where M is the rotating mass of the hollow shell idler at the outer radius, and A is the linear acceleration rate of the web. It is interesting to note that radius cancels out of the formula leaving rotating mass and linear acceleration rate as the important variables.

For both drag and inertia, during acceleration, the higher tension, T_h, is downstream and the lower tension, T_l, is upstream.

Combining formulas 1 and 2, the tension difference across an idler near the end of acceleration is

$$T_h - T_l = Drag + MA \text{ or } T_h = Drag + MA + T_l \qquad \{3\}$$

The capstan formula calculates the tension ratio across an idler necessary to avoid slip. Normally it is shown as a ratio

$$\frac{T_h}{T_l} < e^{\mu\theta} \qquad \{4\}$$

Substituting formula 3 into formula 4 and solving for T_l gives

$$T_l > \frac{Drag + MA}{e^{\mu\theta} - 1} \qquad \{5\}$$

This formula defines a minimum tension required to maintain traction with an idler during acceleration. An interesting note here is the idler's dimensions and mass are factors in both the maximum and minimum tension limits in a given machine. Also, idler velocity is a factor in both increasing bearing drag and lowering the available traction due to air entrainment. Both suggest that, after the web, idler design is the next most important factor in web path design.

In general, air entrainment must be considered when defining a low tension limit. For a given velocity and web - roller combination, there is a minimum tension required to maintain traction with the roller, driven or idler.

Another minimum for tension is to avoid excessive sag in the web between rollers. This is especially a factor in long spans or with high basis weight webs. Assuming a small amount of sag, a formula for the required tension based on an acceptable amount of sag can be calculated as

$$T_{min} > \frac{L^2 BWg}{8S_{max}} \qquad \{6\}$$

We can choose an acceptable amount of sag based on experience. Zero is not an option, but for most low basis weight webs, an S_{max} of 1% of span length or even 0.5% is still a low tension. Excessive sag can lead to swaying and possible edge fold-overs.

The best known low strain limit is the strain required to straighten a cambered web commonly known as the critical strain or critical tension. Given a radius of curvature, ρ, the minimum strain required is

$$\varepsilon_{critical} = \frac{W}{2\rho} \qquad \{7\}$$

This strain leaves the long edge at zero strain and stress, which is not ideal, but any less leaves the edge floppy and the web susceptible to mistracking and wrinkle problems.

These identify common limits of failure for tension and strain, but generally, we would not target our tensions and strains to run right at the limits of failure.

DESIGN LIMITS

Within the bounds of the failure limits, we can define upper and lower design limits that will be safe to run to. We place the design limits so the high to low ratio over driven rollers is not too great and so normal variation of web, equipment and adjustment does not drive us over our failure limits. There are two criteria we can use to find the ratio of the upper over lower design limits. One is to maintain traction over driven rollers and the second is to avoid wrinkles. When a web traverses an S-wrap or single driven roller, it typically has high tension on the upstream side of the roller and low tension on the downstream side. If the T_h/T_l capstan ratio supported by friction and wrap angle is 6, i.e., $T_h/T_l = e^{\mu\theta} = 6$, this is a failure limit for slip and we would normally apply a safety factor of say 2, so that the maximum T_h/T_l over the driven roller would be limited to 3. The safety factor allows for variation in tension and coefficient of friction.

The wrinkle criterion is harder to quantify. When webs go from high tension upstream of a driven roller to low tension downstream of a driven roller, they are going from a more necked down condition to a less necked down condition, i.e., they get wider. Unfortunately, the edges do not always move farther apart and this sudden increase in web width can form buckles or troughs in the web that can collapse into wrinkles on the next roller. The factors that affect this are web width, neckdown and width recovery properties, downstream span length, and web speed. Unfortunately, there is no formula to calculate the safe tension ratio to avoid wrinkles. In an existing machine, it can be found by experiment. Industry rules of thumb range from a 2:1 ratio to a 4:1 ratio. This is an area that could use more investigation.

Highly viscoelastic materials and webs that plastically deform also require low tension ratio over driven rollers to avoid tensioning problems. Web handling science does not help us with a formula here either. My simple test for this is to stretch a web to an initial strain value, hold it for a few moments, relax it, and quickly read the residual strain. The ratio of initial strain to the residual strain captures both viscoelastic and permanent deformation effects. My rule of thumb is to divide this ratio by 2 and use this value as another T_h/T_l ratio limit.

Drive torque may also be a factor for high tension web on large rollers. The tension difference across the roller creates a torque that must be within the drives capabilities.

The ratio between high and low design limits must be less than $e^{\mu\theta}$ and a safety factor based on traction over S-wraps and single driven rollers, and may need to be lower yet based on wrinkles and the web's permanent deformation and viscoelastic behavior. Even if you use nips to achieve high traction capability, you are still limited by wrinkle formation, permanent deformation, and viscoelastic behavior.

ALLOWING FOR VARIATION

The next question is where within the failure limits do we place the design range? Some knowledge of the range of variation of the raw material and equipment properties is needed to completely answer this question. If we assume a design range that is centered within the failure limits, we can design a web path to stay within the design range.

This is easily done in a span plot where we show the failure limits and design range. As shown in Figure 1, the first span's tension will be near the lower design limit.

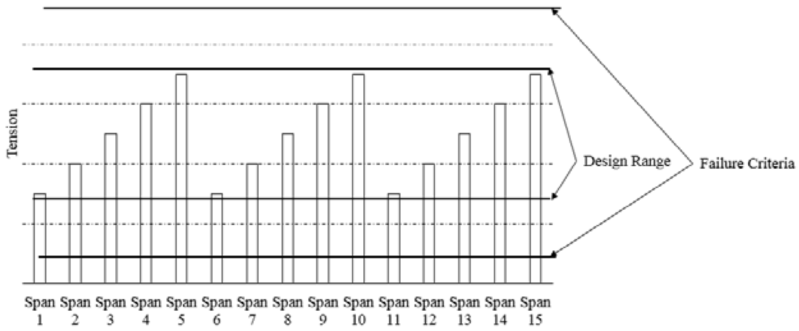

Figure 1 – Initial Span Plot

The next span's tension will be higher by the amount of drag of the idler between. As we continue to add idlers, the tension increases in each span until we reach the upper design limit. This roller, at the end of span 5 in this example, must be a driven roller since one more idler would require tension higher than our upper design limit. Span 6 will start near the lower design limit. By keeping spans 5 and 6 within our design range, we have not exceeded the safe T_h/T_l ratio. Spans 7 through 10 again increase in tension as we add idlers until again, at the end of span 10 we must place a driven roller. As necessary, spans 11 through 15 continue the pattern.

Once the path's tensions are plotted, it is easy enough to model the path using standard web handling formulas in Excel. Using the model, we can do "what if" experiments on the anticipated variation. We can look at the tension ranges that result from high and low modulus, from high and low friction, from the variation of idler drag, from variation of tension and speed settings, from all things we can think of. With enough trials and combinations of variation, we can begin to see what range of tension we can expect over time. Figure 2 shows tension variation plotted on our span plot.

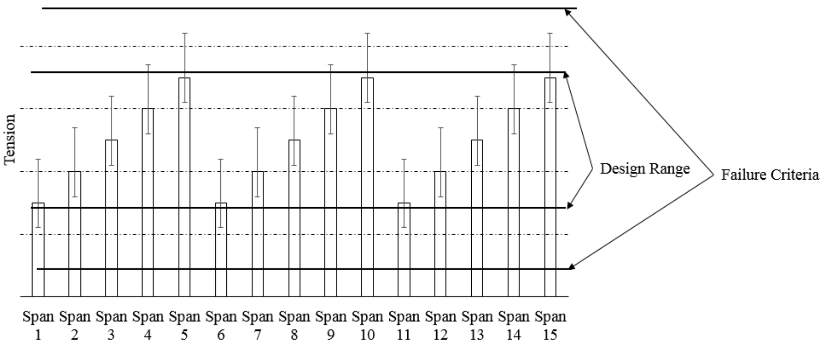

Figure 2 – Initial Span Plot with Variation

If variation had caused tension to exceeded one of the failure limits, we would need to adjust our design range and redesign our web path, or accept the consequences of occasionally hitting a failure limit. In this example, the variation did not exceed the failure limits and this presents some design opportunities. We could accept the design as is. It satisfys the design range requirements and would be robust against variation. Or, we could loosen the specifications on some raw materials possible lowering their cost.

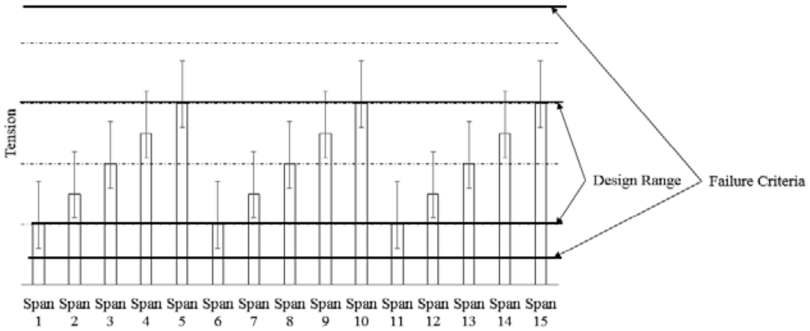

Figure 3 – Optimized Span Plot

Another option, shown in Figure 3, is to lower the design range closer to the lower failure limit. This will also tighten the design range. Generally, lowering and tightening the design range in a web path will reduce the variation of tension due to modulus variation. In addition lower tension means less roller deflection, and less viscoelastic and permanent deformation behavior.

SPECIAL SITUATIONS

There are special situations that we must address in the span plot. The first is tension in the first span required to peel the web from the parent roll. This tension may need to be higher than the lower design limit to overcome blocking. In webs that do not block, 10-15 N/m is normally sufficient to pull the web from the parent roll, but the first span's tension should not be set lower than the lower design limit.

If all we did was to unwind and rewind webs with nothing between, converting would be easy. The processes and transformations along the path may have special tension or strain requirements to work at their best. For example, lamination requires that all webs have the same strain at the lamination roller. Since the lamination rollers are common to all webs, they must have a velocity that keeps the strain and tension of all webs within their own individual design range. Even after lamination, the viscoelastic and permanent deformation behavior of the individual plies must still be considered to avoid inducing curl into the laminate.

Transformations typically alter the properties of the web. The failure and design limits may need to be redefined for the new web based on its new properties. Edge curl is common in laminates due to the difference in neckdown properties of the two webs. This may add a new constraint to the upper tension limit to avoid fold-overs in longer spans. Strips of the laminate of varying lengths can be pulled to varying tensions until the edges curl 90 degrees or more up or down. These combinations of length and tension should be avoided.

CONCLUSIONS

Rules of thumb are common and are difficult to eliminate because there is so much we do not know, or don't have time to find out before we need to make decisions. As web handling research continues, the rules of thumb will continue to be refined and maybe someday, the thumbs will all be replaced with rulers.