WRINKLING MECHANISMS OF WEBS WITH SPATIALLY VARYING MATERIAL PROPERTIES

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ABSTRACT

Webs often include variation in caliper or modulus of elasticity as a result of manufacturing variation. Light-weight nonwoven webs are especially prone to these issues because the variation is proportionally more, relative to the average modulus. It is proposed that the length scale variability in fiber orientation and most importantly mass density extends to the mechanical properties of the web, including the degree of orthotropy and Poisson's ratio (neckdown behavior). Finite element simulations show that materials exhibiting this kind of variability (in MD and CMD modulus, and Poisson's ratio), notably with nominally high and low regions alternating in the MD, leads to trough and wrinkle formation. Multiple simulations with varied material properties have led to a greater understanding of the mechanisms and conditions that cause these types of wrinkles.

NOMENCLATURE

E_1	machine direction Young's modulus of the web, kPa
E_2	cross-machine direction Young's modulus of the web, kPa
σ_1	machine direction web stress, kPa
σ_2	cross-machine direction web stress, kPa
ϵ_1	nominal machine direction strain
ϵ_2	nominal cross-machine direction strain
ν_{12}	Poisson's ratio
G_{12}	shear modulus of the web in the MD/CMD direction, kPa
G_{13}	shear modulus of the web in the MD/thickness direction, kPa
G_{23}	shear modulus of the web in the CMD/thickness direction, kPa
O	degree of orthotropy (E_1/E_2)
α	modulus variation (defines ~2 St. Dev., as % + or – from the mean)
h	base web thickness, mm
L	span length, mm

W	total unstrained web width, mm
R	roller radius, mm
V	web velocity, mm/s
μ	static coefficient of friction between rollers and web

INTRODUCTION

Nonwoven webs consist of many polymer strands loosely and semi-randomly over-laid and then intermittently point bonded. Therefore, nonwoven webs are inherently heterogeneous and random in nature. The number and size of fibers, their orientation distribution, and the geometry and the pattern of point bonding are known to influence the overall properties of the material. Similarly, variation in the making process would be expected to cause local variation of the properties.

There can be gradual differences across a material's width (drive vs. operator side) or differences in time (from the beginning to the end of a roll) but the current focus is on semi-random and higher frequency variation of immediately adjacent regions – such as two points that are only a few centimeters away from each other in the machine direction (MD) or cross-machine direction (CMD).

Wrinkles or the tendency to wrinkle is a significant detriment to the manufacturing processes used to construct products from webs. With significant wrinkling, the edges of webs will move toward the center and the web can mistrack in the CMD, creating subsequent problems in combining or aligning multiple web. Some wrinkles, if they survive the process to the finished product, are also unsightly to the consumer.

Observations on manufacturing lines suggest that increases in local basis weight variation make webs more likely to wrinkle and harder to convert in a flat, unfolded state. These problems become especially apparent as basis weights trend downwards – presumably because the relative variation (as a percentage of the average) is higher and because the material is more flexible in bending.

Nonwoven webs are often orthotropic and have varying amounts of neckdown or Poisson's-like behavior. These webs also have regions of high and low basis weight where more or fewer fibers happen to overlap. These localized mass variations, and their relative effect on the creation of wrinkles, are the focus of this paper. Finite element simulation was used to study the effect of material variation, Poisson's ratio, and orthotropy on trough and wrinkle formation.

SIMULATION SETUP AND METHOLOGY

A single span and driven rollers are used for each simulation. The span length, web width, web thickness, roller diameter, roller/web coefficient of friction and web velocity are held constant. The simulations only differ in the material properties comprising the web. The Poisson's ratio (ν_{12}), degree of orthotropy (O), and modulus variation (α) were the only things that varied between simulations. Importantly, each of the different materials in the simulations have the same average modulus in the CMD and therefore the same average bending stiffness in the CMD direction.

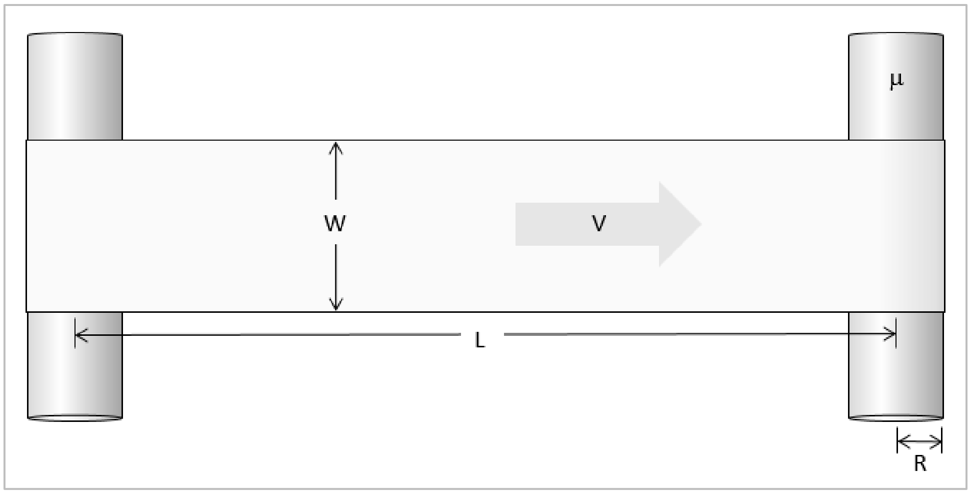


Figure 1 – Fixed Parameters for Web and Path Geometry

A key feature of the simulations is that they use web materials with a semi-random, spatially varying modulus that varies in both the MD and CMD. This pattern of spatial variation is based on the characterization of light transmission scans of a real nonwoven web. Characteristic lengths that describe the variation in the MD and CMD (of a small sample) are then used to generate a Gaussian random field for a larger web for the purposes of the simulations, Brett [1], Haran [2], and Holmes [3]. This pattern undergoes a Mori-Tanaka homogenization process to ensure that the bulk properties of the varied web remain the same as the intended average, Torquato [4]. Each simulated web has the same pattern of variation, however, for different cases the pattern can be amplified or rendered flat by assigning very different materials (amplified) or identical materials (flat) to the different regions of the pattern.

The following example case will illustrate how the variation is defined: Given a material with an average modulus of 100 and a modulus variation of 40% -- the lowest (basis weight) regions in the web will have a modulus of ~60 and the highest (basis weight) regions in the web will have a modulus of ~140. In Dassault's Simulia FEA software (ABAQUS), the pattern is generically defined with what is known as a field variable and different material models can be assigned to different field values. Intermediate materials (with field values between the ones assigned) are linearly interpolated between the materials that are defined. This field value for a portion of the web is shown in Figure 2.

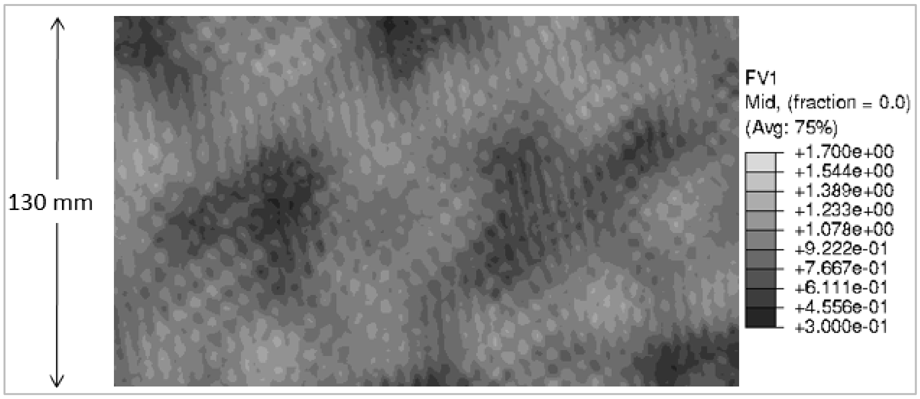


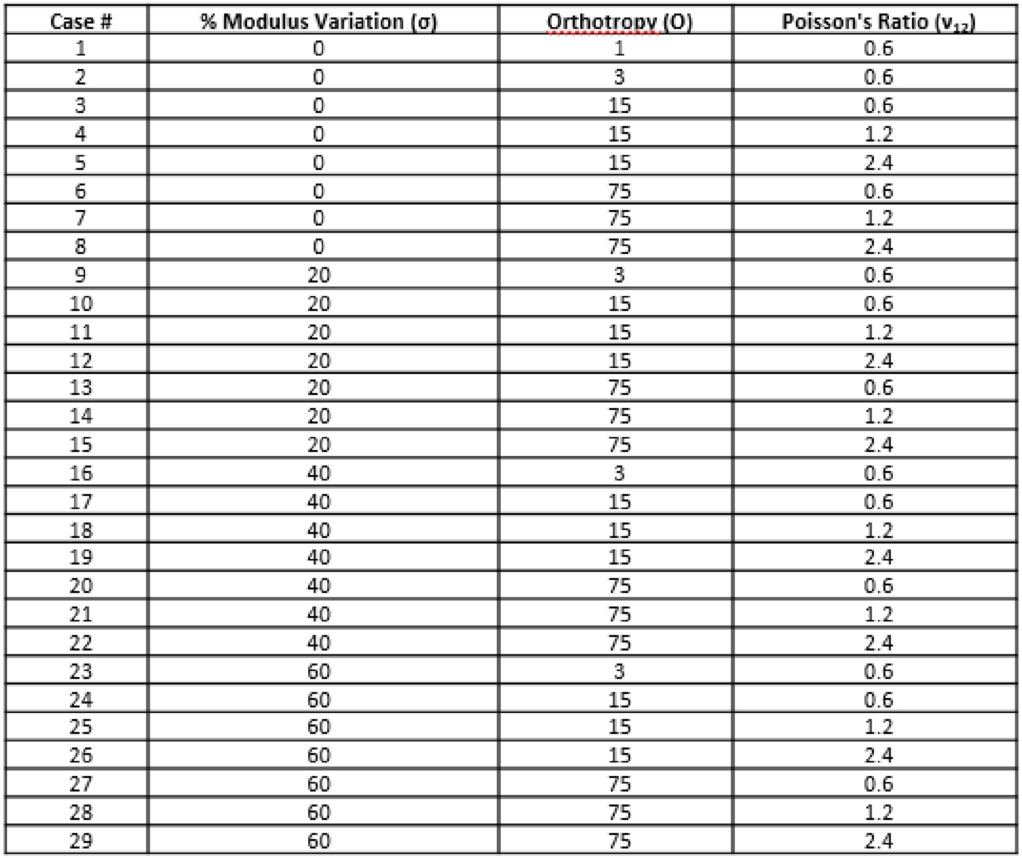
Figure 2 – Section of Web with Contours Showing the Abaqus Field Value (FV1)

Experimental Design

A full factorial design was used to explore the described web material differences – specifically, the Poisson's ratio, degree of orthotropy, and amount of modulus variation. Table 1 outlines the fixed parameters and each of the variable ranges. There are, however, material stability criteria that limit testing of the full space outlined by the ranges of those variables. Material stability criteria indicate that Poisson's ratio must be less than the square root of E_1/E_2. Any cases that violated this criteria were simply removed from the study. Table 2 shows all of the cases simulated and analyzed for this study.

Parameters	**Value**
ε_{MD} ($\Delta L/L$)	0.015
W (mm)	135
h (mm)	0.0665
R (mm)	25
V (mm/s)	8000
μ_s (COF)	0.3
$E_{2\,(CMD)}$ (kPa)	6015
L (mm)	700
Variables	**Range**
O (E_1/E_2)	1 - 75
σ (+/- % from mean)	0 - 60
ν_{12} ($= -\epsilon_2/\epsilon_1$)	0.6 – 2.4

Table 1 – Web Parameters and Variable Ranges



Case #	% Modulus Variation (σ)	Orthotropy (O)	Poisson's Ratio (ν_{12})
1	0	1	0.6
2	0	3	0.6
3	0	15	0.6
4	0	15	1.2
5	0	15	2.4
6	0	75	0.6
7	0	75	1.2
8	0	75	2.4
9	20	3	0.6
10	20	15	0.6
11	20	15	1.2
12	20	15	2.4
13	20	75	0.6
14	20	75	1.2
15	20	75	2.4
16	40	3	0.6
17	40	15	0.6
18	40	15	1.2
19	40	15	2.4
20	40	75	0.6
21	40	75	1.2
22	40	75	2.4
23	60	3	0.6
24	60	15	0.6
25	60	15	1.2
26	60	15	2.4
27	60	75	0.6
28	60	75	1.2
29	60	75	2.4

Table 2 – Simulation Cases

Simulation Computational Parameters

Dassault Systèmes' ABAQUS/Explicit version 2016 software was used as the finite element analysis tool. To allow for steady state conditions in the web the simulation were run for 0.75 seconds. Shell elements with a mesh size of 0.75 mm X 0.75 mm were used.

Measuring Wrinkle Characteristics

Out-of-plane motion is often the precursor to the formation of folds in a web. This out-of-plane motion is first seen as troughs, or to be more precise, a sinusoidal curve when viewed as a cross-section (the web being cut across in the CMD direction). The amplitude and wavelength of these curves likely relate to wrinkling tendency, and while higher amplitude is certainly worse, it is less clear how wavelength relates. One would surmise that high amplitude, in combination with low wavelength, is the worst case and that a ratio of amplitude to wavelength makes sense when trying to characterize the tendency to wrinkle.

This analysis posits a quantitative predictor of the tendency to wrinkle. The predictive measure is a ratio of the amplitude to wavelength with higher values indicating a greater likelihood to wrinkle. The CMD and out-of-plane positions are measured at a fixed point in time near the end of the analysis – resulting in data (and plots) of the web cross-sectional shape at mid-span (example plots shown in Figure 3). This data is measured for the range (and divided by 2 to get the approximate amplitude) and also spectrally analyzed to determine the primary wavelength. The proposed measure (amplitude/wavelength) was then compared to a qualitative visual grading of the webs likelihood to wrinkle (Figure 4). Also see Table 3 for a description of the grading criteria.

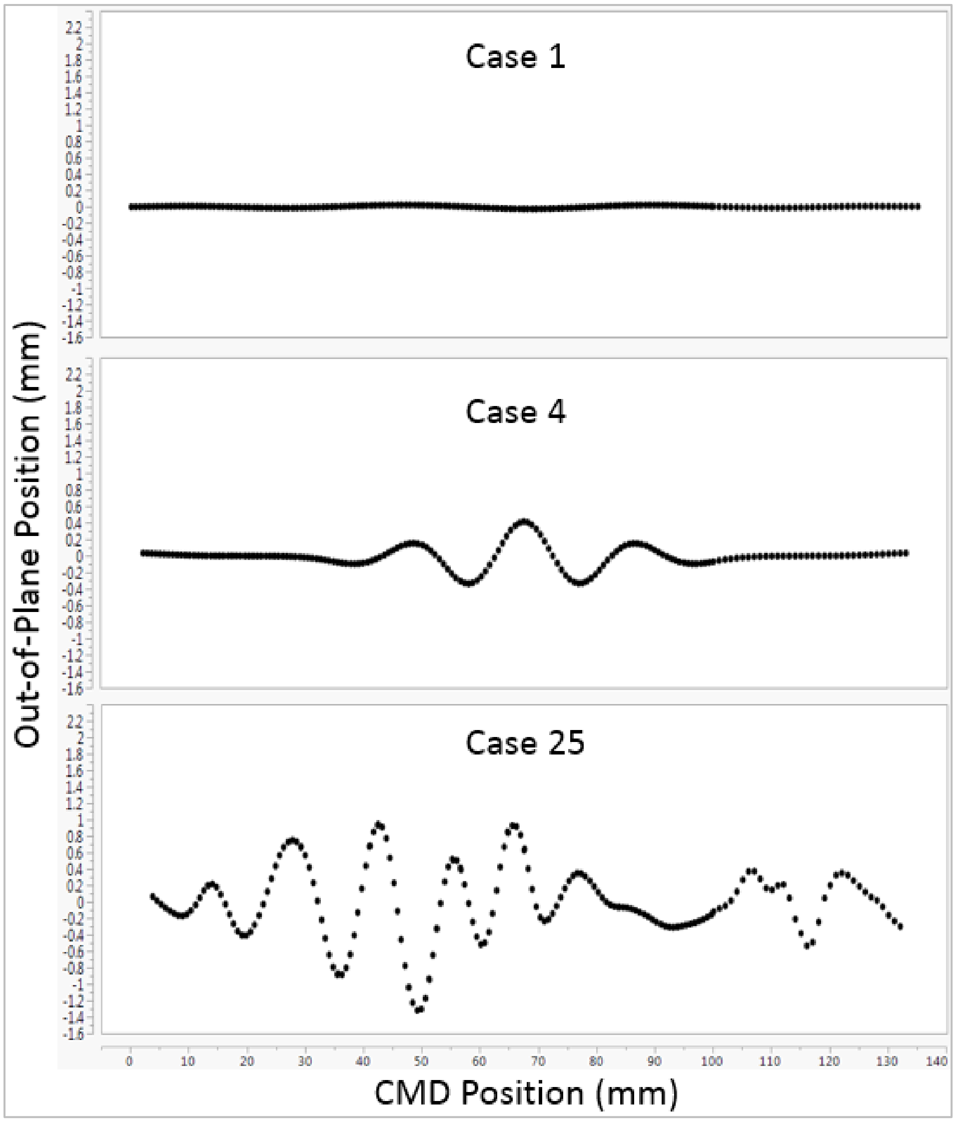


Figure 3 – Examples of Web Cross-Sections at Mid-Span for Cases 1, 4, and 2

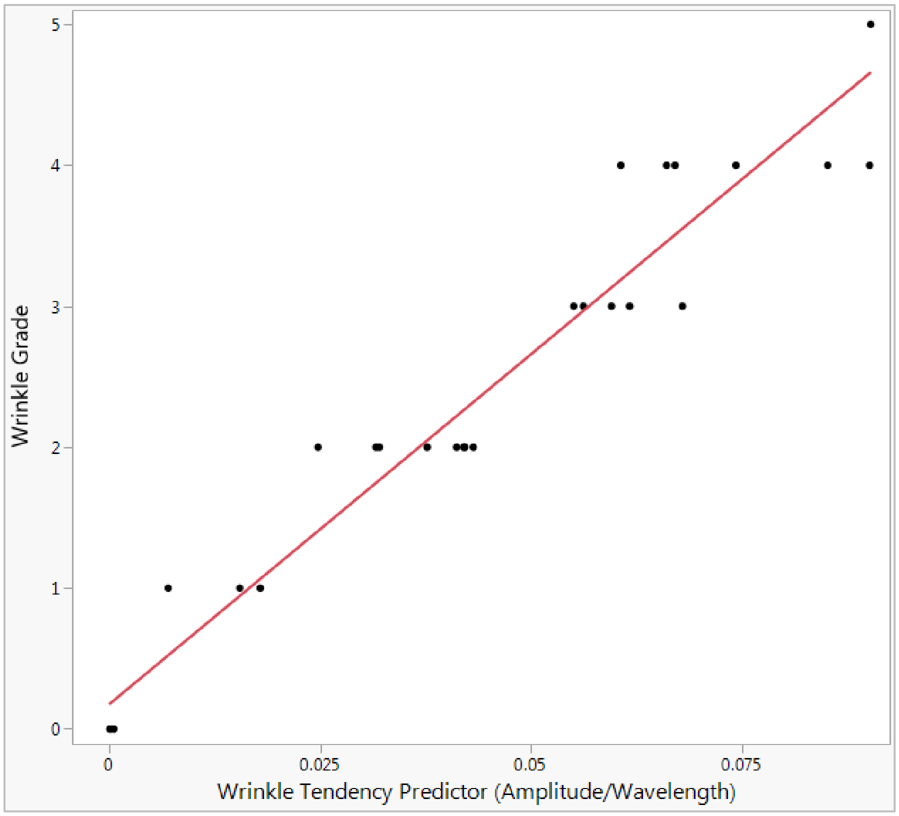


Figure 4 – Plot Showing Correlation of the Measured Wrinkle Tendency Predictor and the Subjective Wrinkle Grade

Wrinkle Grade	Characteristics
0	Very flat, no apparent troughs
1	Slight troughs, centered/symmetric
2	Moderate troughs, some asymmetry
3	Major troughs, asymmetric and chaotic
4	+ Wrinkles forming on roller
5	+ Fold-overs forming on roller

Table 3 – Visual Wrinkle Grading Criteria

Data Analysis

Using the design variables (modulus variation, orthotropy, and Poisson's ratio) a Gaussian process model was fit to the wrinkle tendency prediction measure, Joseph [5], Ba [6]. This statistical modeling exercise allows assessment of relative importance and interaction between the variables.

RESULTS AND DISCUSSION

What Aspects of the Material Properties Are Most Influential?

Material modulus variation had the largest impact on the formation of troughs, and in the highest variation cases, the formation of wrinkles and folds. A modulus variation of 60% created wrinkles (and in one case a fold) whereas cases at 40% variation had large troughs but no wrinkles. Element size, relative to the radius of web curvature is an important consideration. Previous work, not included in this paper, has shown that if elements bend more than approximately 20 degrees relative to each other they become stiffer in bending. At an element size of 0.75 mm the web can bend about a radius of 4 mm without significant effect. A web radius smaller than 4 mm (as will be experienced in wrinkles and folds) will bend the web more than 20 degrees and the degree of curvature and wrinkling will be lessened. The rank order with respect to the amount of wrinkling is not expected to change but real webs under similar conditions and with similar properties would be more likely to wrinkle than as shown in the simulations.

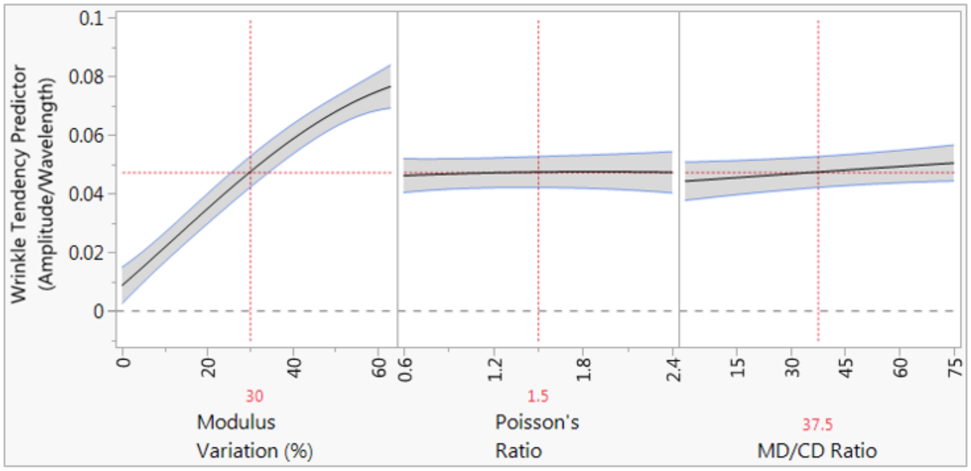


Figure 5 – Statistical Model Showing Importance of Modulus Variation on Trough and Wrinkle Formation

Why Does Spatial Variation of Material Properties Create Wrinkles?

Both the MD and CMD dimension are important when considering the mechanisms that cause troughs and wrinkles. CMD differences in modulus are known to cause bending and mistracking, especially in relatively long spans, leading to shear strain and possibly troughs if the bending stiffness of the material is low enough. Consider the thought experiment where a web is split into two regions with different MD modulus (Figure 6). Regions with high Poisson's ratio and/or low MD modulus contract in the CMD more than do low Poisson's ratio and/or high MD modulus regions, therefore causing a differential in CMD strain. The differential in CMD strain likely leads to buckling of the region with higher MD modulus and/or lower Poisson's Ratio (Figure 6). This effect should hold true for any web with alternating modulus or Poisson's ratio variation in the MD.

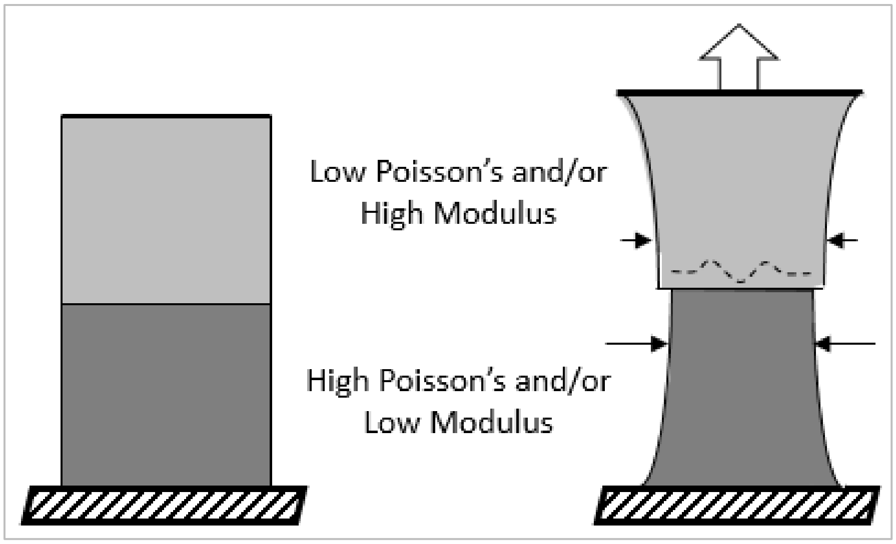


Figure 6 – Diagram Showing an Extreme Variation Case Where Two Different Webs Are Linked Together in the MD and Put under Tension

Does a Higher Poisson's Ratio Increase Formation of Troughs and Wrinkles?

Consider the example of a uniform web material with a Poisson's ratio of zero that is gripped with clamped ends and placed under tension. This uniform material will not form troughs as long as Poisson's ratio is also zero. As Poisson's ratio is increased and the test is repeated, compressive stresses will form in the web and there will be some critical value at which the material buckles and forms troughs. Also consider an example with a web material that is specially clamped at its ends to freely allow CMD contraction. Previous simulation work, not included in this paper, shows that loading of this type will not produce any troughs, regardless of Poisson's ratio. Therefore, the formation of troughs in a uniform web under tension is very dependent on both a positive Poisson's ratio and the specific CMD boundary conditions. Now consider one more example where a web material with a Poisson's ratio of zero also has a modulus that spatially varies. This type of web material should avoid the troughs and wrinkles that are due to nominally low and high modulus regions in series as no CMD strain differential will develop when the sample is placed under MD tension.

The results of this paper show no wrinkles as Poisson's ratio and modulus variation both approach zero, however, at higher levels of modulus variation the wrinkle tendency does not seem to converge at zero (as Poisson's ratio goes to zero). There is also a reverse trend in which increasing Poisson's acts to reduce wrinkle tendency. Figure 7 shows how this Poisson's effect differs at high and low amounts of modulus variation.

There appears to be a slight decrease in wrinkle tendency when changing from a Poisson's ratio of 0.6 to 2.4 at a modulus variation of greater than 50%. The small effect may be caused by interactions between the troughs that naturally form (in even a uniform web with positive Poisson's ratio) and the troughs that form due to different modulus materials in series. If these effects overlap they may add or subtract depending on the phasing and wavelength.

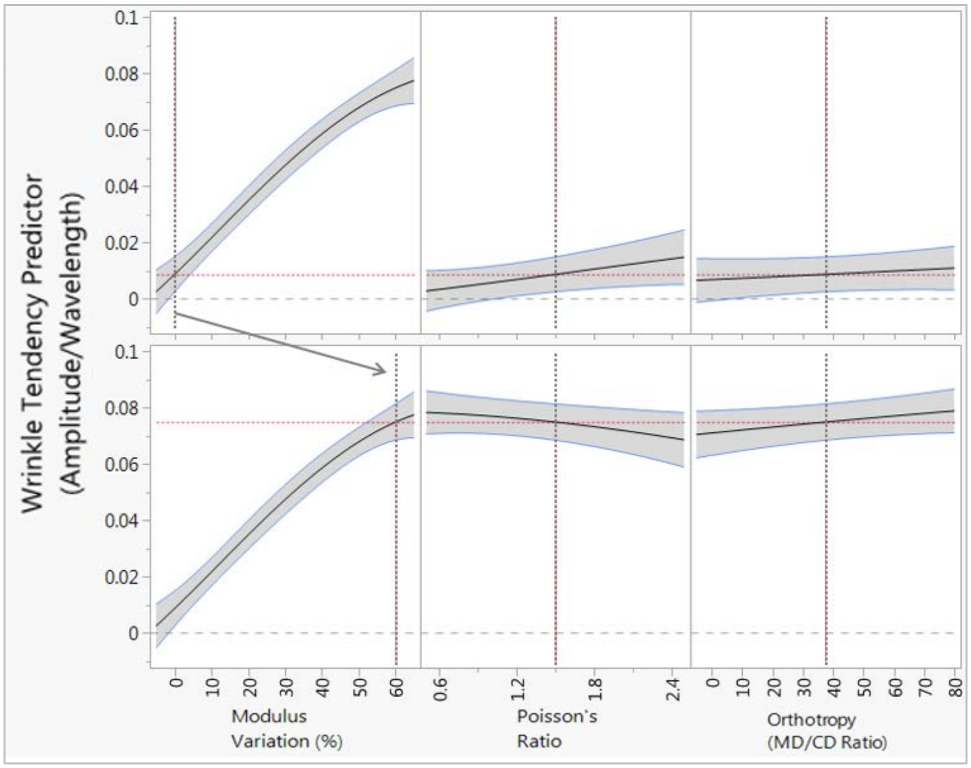
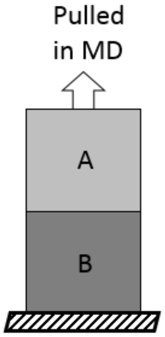


Figure 7 – Impacts on Wrinkle Tendency for 0% and 60% Modulus Variation

Are There Unique Materials That Resist Wrinkles?

Materials that are stiff in bending and/or perfectly uniform in their properties are obvious candidates for wrinkling resistance. However, these options are typically associated with higher basis weight materials that are more expensive. Webs that resist wrinkling without increasing basis weight are harder to make but of course more desirable. By reasoning presented in this paper, any material that has a Poisson's ratio of zero should be resistant to spatial modulus variation. Regardless of the degree of variation or the amount of strain there will be no differential in CMD strain.

Similarly, there could be an opportunity to design materials that have neckdown behavior that varies with modulus. If the Poisson's ratio of a material is proportional to its MD modulus such that the quantity ν_{12}/E_1 remains a constant throughout the nominally low and high modulus regions the material will have similar immunity to differential strain in the CMD (Figure 8). This approach may help protect against MD variation in modulus but have no impact against CMD variation or other mechanisms that cause troughs or wrinkles.



The following relates the MD stress to MD strain: $\sigma_1 = \epsilon_1 E_1$

The following relates the MD strain to CMD strain: $\epsilon_2 = -\nu_{12}\epsilon_1$

Materials A and B have the same width, thickness, and tension.
Therefore: $\sigma_{1A} = \sigma_{1B}$

Substituting: $\frac{-\nu_{12A}\cancel{\sigma_{1A}}}{E_{1A}} = \frac{-\nu_{12B}\cancel{\sigma_{1B}}}{E_{1B}} \Rightarrow \frac{-\nu_{12A}}{E_{1A}} = \frac{-\nu_{12B}}{E_{1B}}$

Figure 8 – Diagram and Equations Showing Criteria to Avoid Differential CMD Strain

CONCLUSIONS

This paper studies the impact of spatial material property variation – specifically MD modulus variation, Poisson's ratio, and orthotropy. 29 different materials were simulated to better understand the drivers of wrinkling problems that are common in web handling. To this end a wrinkle prediction measure was proposed as the ratio of amplitude over wavelength of the waves that form in a tensioned web. This measure correlates well with a subjective grading of the troughs and wrinkles that form in each of the 29 simulations. Spatial variation of MD modulus was the biggest driver of wrinkling issues with variation over 60% (if not lower) causing actual wrinkles and fold overs on the rollers. Poisson's Ratio seems to have a lesser and mixed impact on wrinkling but would be interesting to study further.

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