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Breaking the fiber quality ceiling: Limitations of cotton fibers bundle testing

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Cotton Field Blooming

Hypotheses

- Genetic variability of within-plant variability do exist.
- Therefore it should be possible to breed for new cultivars that exhibit less variability of fiber properties within-plant.
- This should lead to lower variability within-bale and ultimately to better yarn quality especially for spinning technologies that are very sensitive to fiber properties distributions (among fibers) such as air-jet.

Hypotheses

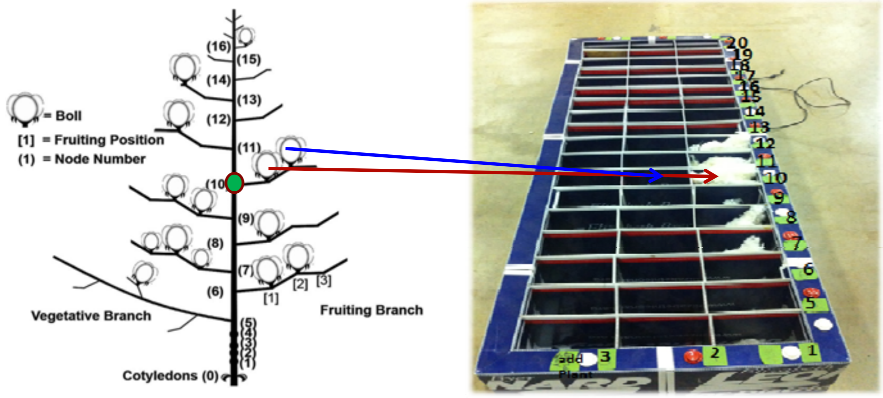
- If these hypotheses are confirmed, then there will be a need to develop high speed measurements of distributions rather than simply assessing the value of the bulk as we currently do with HVI.

Within-plant variability

Protocol

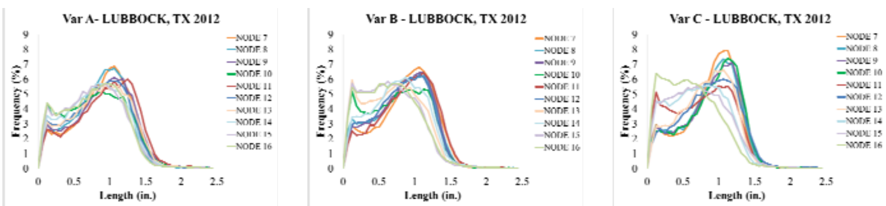
- Grow a series of varieties in several environments (space and time).
- Harvest each boll (box picking).
- Gin and test the lint produced with AFIS.

Box picking



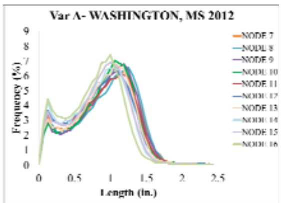
Length Distributions

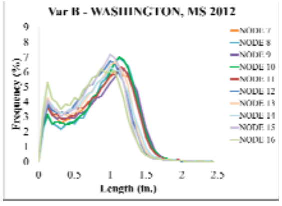
Within-plant fiber length distribution of first position bolls from Lubbock, TX in 2012.

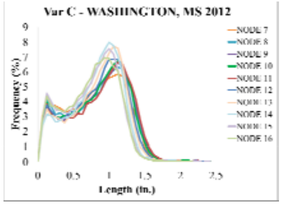


Length Distributions

Within-plant fiber length distribution of first position bolls from Washington, MS in 2012.

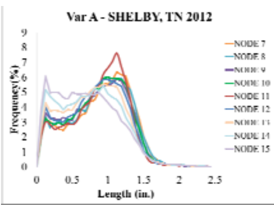


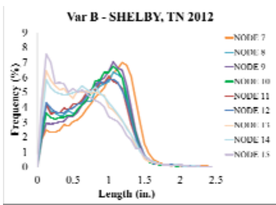


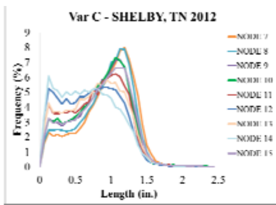


Length Distribution

Within-plant fiber length distribution of first position bolls from Shelby, TN in 2012.







Conclusion

- Genetic variability of within-plant variability do exist.
- In good growing conditions, all varieties perform reasonably well but in poor conditions Variety A has a clear advantage.
- Therefore it should be possible to breed for new cultivars that exhibit less variability of fiber properties within-plant. It is reasonable to hypothesize that fiber properties distributions may have an impact on yarn quality and processing efficiency.

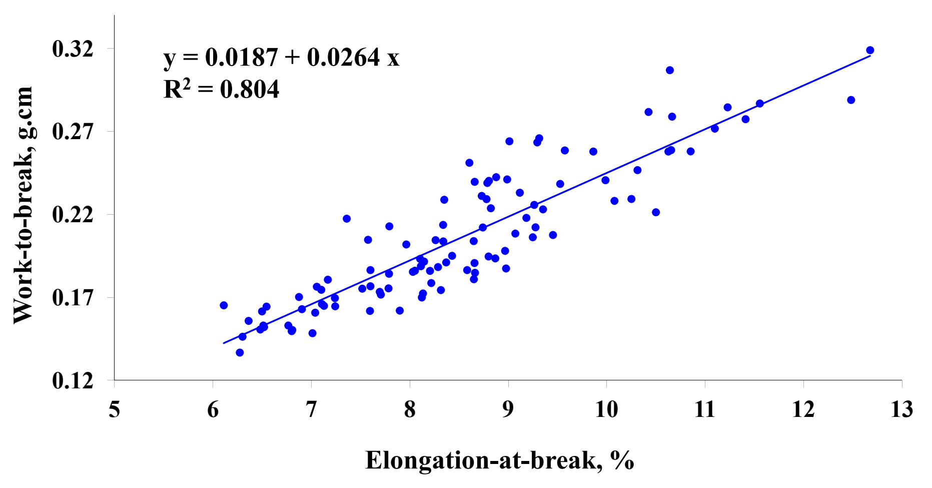
Distributions of fiber properties within-sample: An example

FAVIMAT on the 104 (average values)

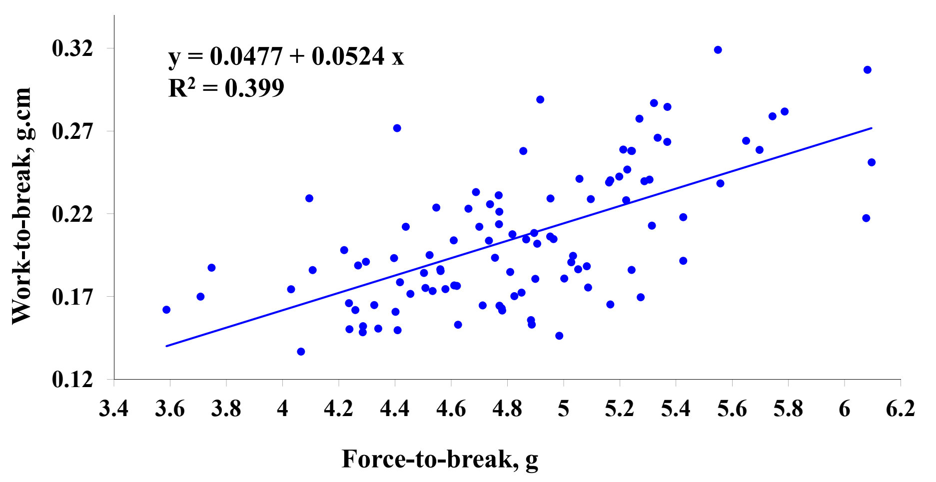
Introduction

- This study was performed on the 104 reference cottons for maturity described by Hequet (2006). The samples were tested with the FAVIMAT (gauge length = 10 mm, pre-tension = 0.2 cN/tex, and testing speed = 20 mm/min) with three replications of 150 fibers.

FAVIMAT:
Elongation-at-break vs. Work-to-break



FAVIMAT:
Force-to-break vs. Work-to-break



FAVIMAT

- **These results show an excellent linear relationship between elongation-at-break and work-to-break (r^2 = 0.804) and a relatively poor linear relationship between force-to-break and work-to-break (r^2 = 0.399).**

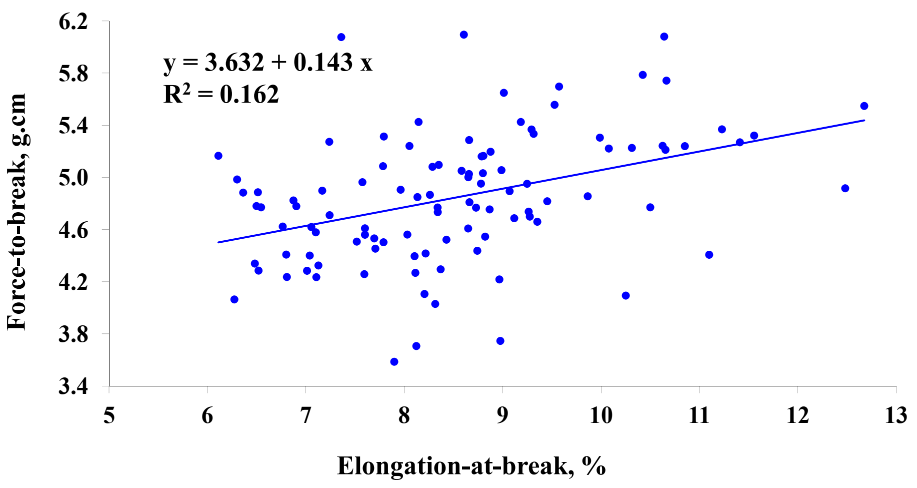
- **It seems that, for this set of samples, the main contributor of the work-to-break is the elongation-at-break (please recall elongation is not currently reported by HVI) .**

FAVIMAT

- **For elongation-at-break the range of variation among samples is quite large (from 6.1% to 12.7%) while it is narrower for force-to-break (from 3.6 to 6.1 g). It confirms that there is a wide range of variability available in the current cotton germplasm for fiber elongation (the 104 were commercial cotton bales).**

- **Unfortunately, at this time, most of the cotton breeders concentrate their effort on improving strength and ignore elongation.**

FAVIMAT:
Elongation-at-break vs. Force-to-break

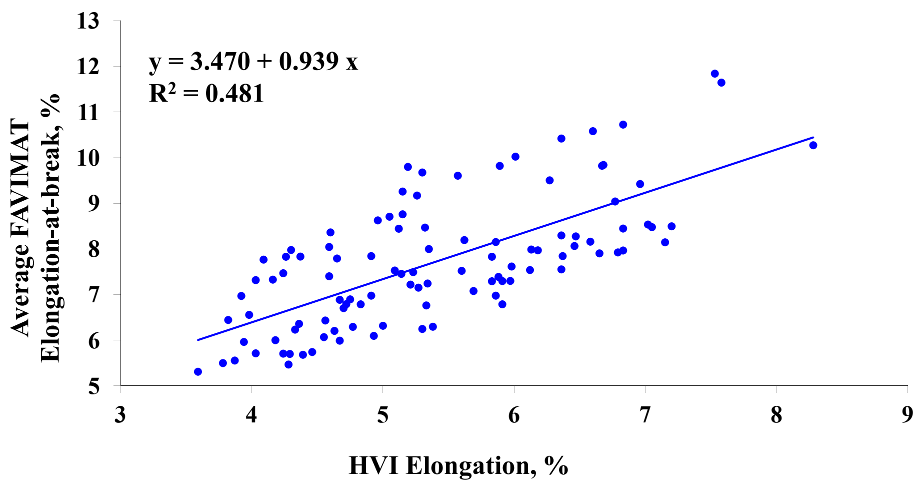


FAVIMAT

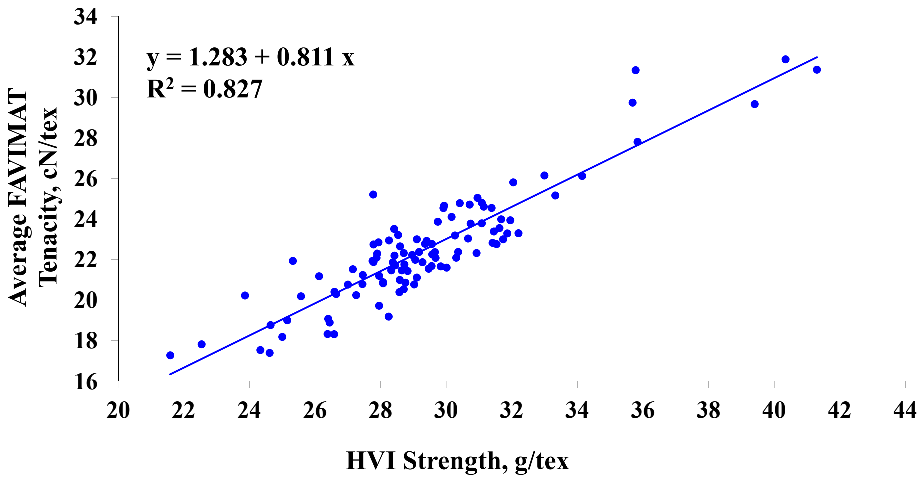
- The relationship between force-to-break and elongation-at-break is quite weak ($r^2 = 0.162$) and positive.
- It is well documented that with bundle tests such as HVI the same relationship is weak and negative (also true for this set of samples $r^2 = 0.126$).
- This negative relationship is one of the reason why the cotton breeders do not work on elongation. They are concerned that improving elongation will result in lower tenacity and possibly discounts.

Relationships FAVIMAT - HVI

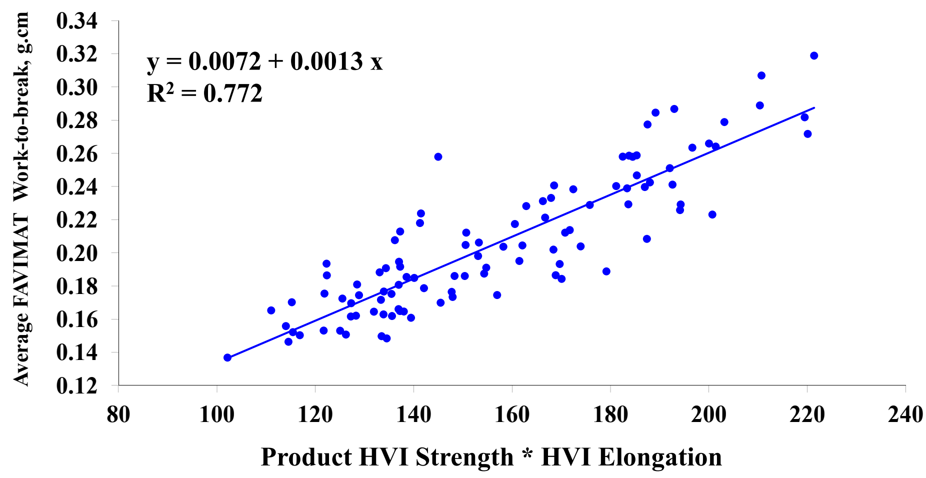
HVI Elongation vs. FAVIMAT Elongation



HVI Strength vs. FAVIMAT Tenacity



HVI Strength * HVI Elongation (substitute for HVI Work-to-break) vs. FAVIMAT Tenacity



FAVIMAT vs. HVI

- The relationships between average FAVIMAT tensile properties and HVI bundle properties are all linear with a positive slope and a rather good coefficient of determination (except elongation).
- Why do we have a positive relationship among samples with the FAVIMAT (arithmetic average of all fibers tested) and a negative one with the HVI (bundle test)?

FAVIMAT vs. HVI

- What are the main differences between a tensile bundle test and the arithmetic average of individual fibers tensile tests?
- For the average of individual fibers tensile tests there is no interaction effect.
- For a bundle test, we have to take into account the possible interactions among fibers during the test that leads to the breakage of the bundle.

FAVIMAT vs. HVI

- Among the main effects are:
  - tenacity,
  - elongation,
  - work-to-break of the individual fibers,
  - friction among the fibers in the bundle (related to the number of fibers in the bundle, the residual crimp, and the wax content),
  - and the standard deviation of each of these factors.

FAVIMAT vs. HVI

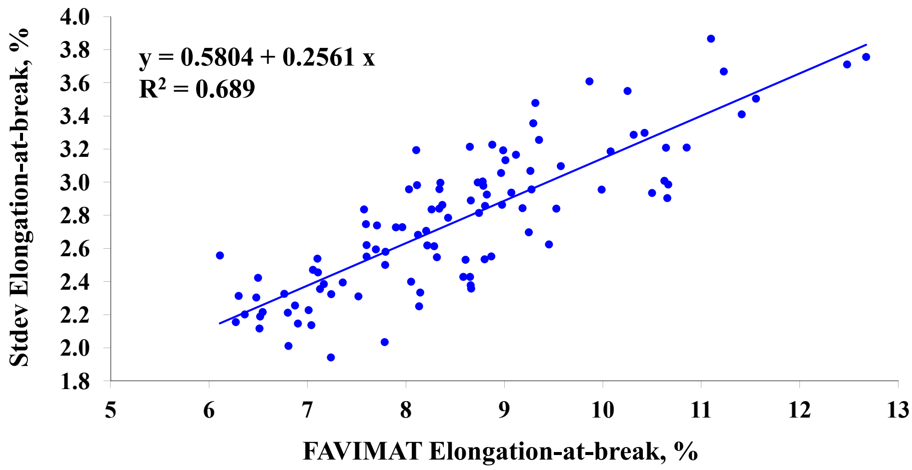
- Intuitively we understand that a bundle with a large variation in elongation from fiber to fiber will not behave the same as a perfect bundle where all fibers are identical even if the elongation averages are identical (all other fiber properties being constant).

FAVIMAT vs. HVI

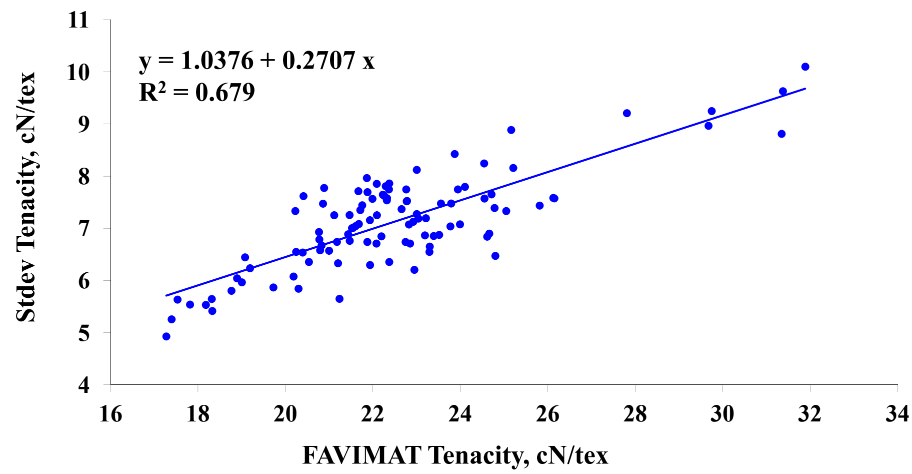
- The bundle with a large variability in elongation may be weaker because the stress applied to the bundle is exerted first on the low elongation fibers instead of being shared by all fibers equally (assuming all fibers are clamped on both ends).
- The low elongation fibers break first, then the full force is applied to the remaining fibers and due to a cascading effect the whole bundle breaks.

Variability among fibers of the tensile properties

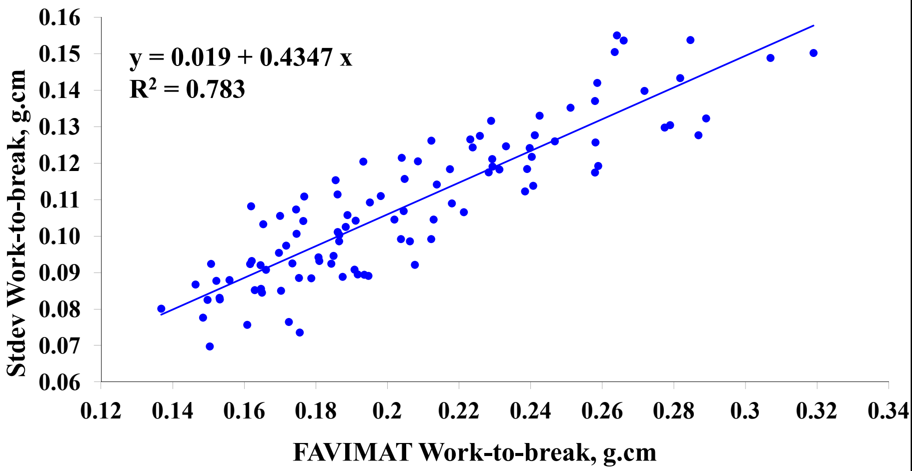
FAVIMAT Elongation-at-break vs. FAVIMAT Stdev Elongation-at-break (among fibers)



FAVIMAT Tenacity vs. FAVIMAT Stdev Tenacity (among fibers)



FAVIMAT Work-to-break vs. FAVIMAT Stdev Work-to-break (among fibers)



FAVIMAT: Averages vs. Standard Deviations

- **The relationships between average FAVIMAT tensile properties and their standard deviations are all linear with a positive slope and a high coefficient of determination (non-Gaussian distributions).**
- **Therefore, cottons with high elongation and high standard deviation may tend to have lower bundle tenacity.**

FAVIMAT: Averages vs. Standard Deviations

- However, during fiber processing the stress is not applied to bundle of fibers but to individual fibers or small tufts of fibers.
- Therefore, the individual fiber's work-to-break is extremely important to prevent fiber breakage.
- Stronger fibers tend to have higher elongation which results in better work-to-break. This could lead to lower fiber breakage during processing.

FAVIMAT: Averages vs. Standard Deviations

- The current practice of ignoring fiber elongation or worse of eliminating high elongation lines because of the perceived negative effect this may have on bundle strength may lead to lower work-to-break.
- Lower work-to-break will lead to more fiber breakage and therefore higher short fiber content.

Distributions

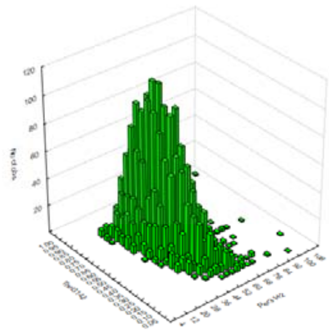
FAVIMAT and Cross-sections: Distributions

- Four samples were retested on the FAVIMAT with a 3 mm gauge at the FBRI (2,000 fibers per sample).
- Bales 3142 and 3016 have exactly the same micronaire reading (4.28) but bale 3142 has a smaller fiber perimeter and better maturity than bale 3016.

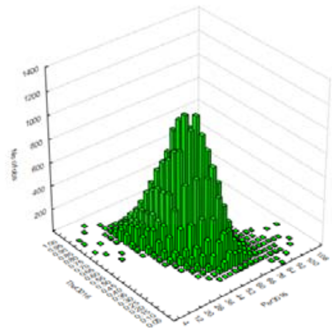
Bivariate histograms: Theta - Perimeter

Micronaire = 4.28

Cotton 3142



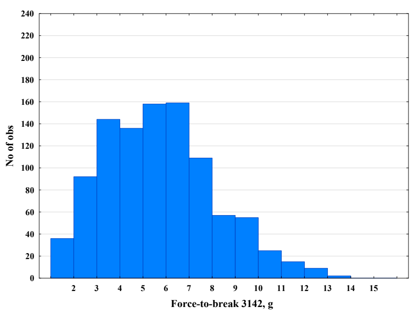
Cotton 3016



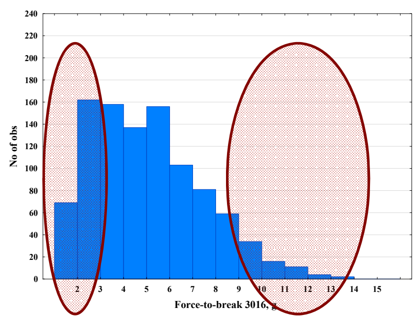
Histograms: Force-to-break

Micronaire = 4.28

Cotton 3142



Cotton 3016



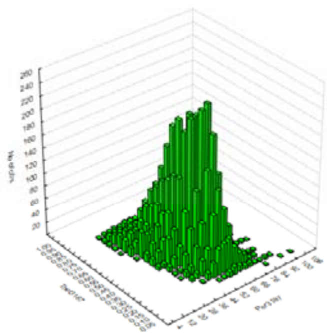
Bale 3016 has an excess of very low force-to-break fibers (3 g and below) and a deficit of very strong fibers (9 g and above) compared to bale 3142.

FAVIMAT and Cross-sections: Distributions

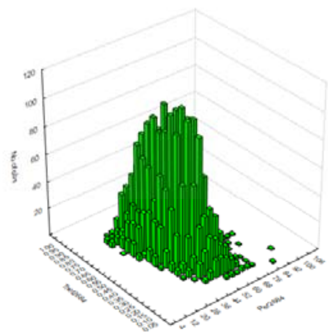
- Bales 3187 and 2684 have a discount micronaire (3.41 and 3.32 respectively) but bale 3187 has a very large excess of immature fibers compared to bale 2684.
- This translates logically into a much larger number of fibers with low force-to-break for bale 3187.

Bivariate histograms: Theta - Perimeter

Micronaire = 3.41
Cotton 3187



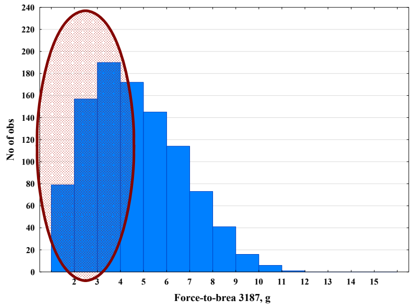
Micronaire = 3.32
Cotton 2684



Histograms: Force-to-break

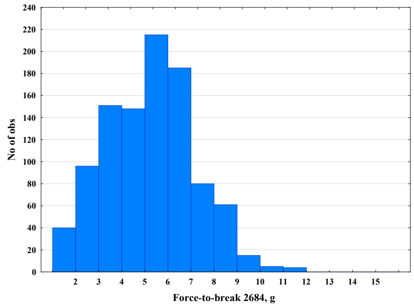
Micronaire = 3.41

Cotton 3187



Micronaire = 3.32

Cotton 2684

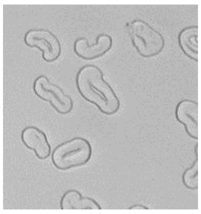


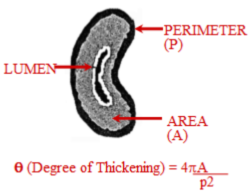
Conclusion

- **Based on cross-sections, the differences between the two types of cotton (more mature vs. less mature for a given level of micronaire) are quite obvious.**
- **Even a premium micronaire range cotton may have a very significant part of its fiber population in a very low force-to-break range.**
- **This type of cotton will not behave well when submitted to mechanical processing (fiber breakage).**

Within fiber variability

Maturity: Cross-sections method

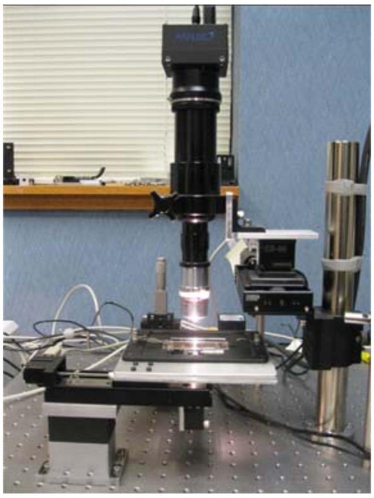




Current reference method: cross sections

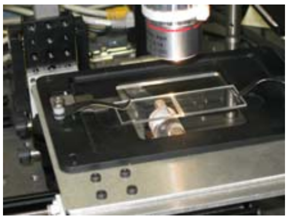
- Employs microscopic image analysis of cotton fiber cross sections
- Bundles of 500 fibers are cut with a microtome and prepared on a slide
- Features of interest:
  - *Perimeter*
  - *Area of cell wall (thickness)*
- Maturity, θ, is the ratio of the area of a circle with perimeter, P, to that of the area of the cell wall, A

Prototype system



Prototype system

- Uses line scan camera and moving stage to capture longitudinal images of a single fiber
- Resolution: 1µm/pixel



Features extraction

- Images are broken into *tiles* each containing ~150µm fiber segment
- 13 features are extracted from each tile
  - *Standard features:* a set of 9 features based on the physical properties of a fiber (min/max/avg width, min/max/avg intensity, etc.)
  - *Texture features:* a set of 4 Haralick features

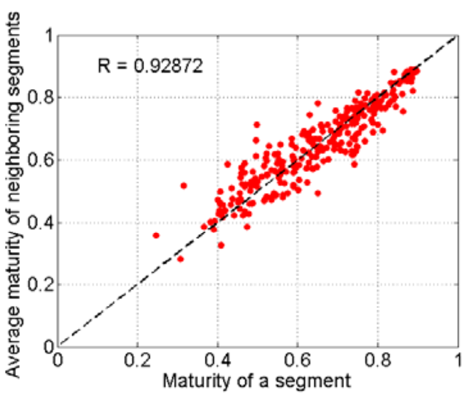
Prior work: Transfer Learning

Prior work (Shahriar, 2012) employed transfer learning

- Transfer learning maps data in a source domain (cross section features) to a target domain (image features)
- Once the system is trained, a resulting regression equation takes image features and produces a maturity value
- Maturity of each image tile is evaluated

Prior work: Transfer Learning

Finding: **maturity for a single fiber appears to vary more than previously considered**



Shahriar, 2012

Investigation of Intra-fiber Variability of Maturity

Validation of maturity variability

Confocal microscopy as a validation method

- Current reference method (cross sections) is impractical as a validation method
- Using confocal microscopy we can create a virtual 3D model of the cotton fiber
  - *Use image analysis techniques to segment the fiber within the image volume*
  - *Measure perimeter and area of virtual cross sections*

Confocal microscopy

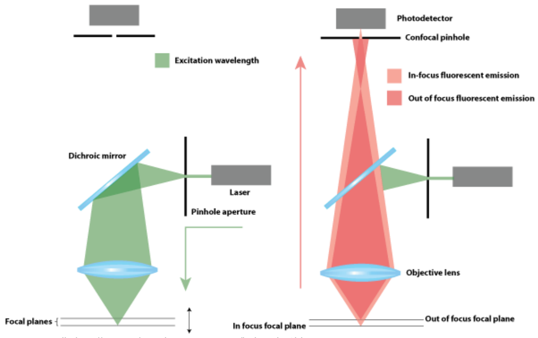


Image credit: http://www.scienceinyoureyes.com/index.php?id=71

- Laser provides excitation photons
- Lasers controlled by galvanometric mirrors in raster scan fashion
- Emission photons pass through confocal pinhole

3D Image formation (optical sectioning):

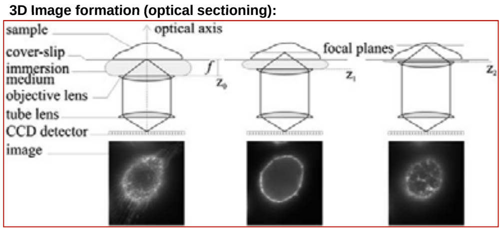
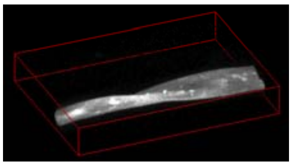
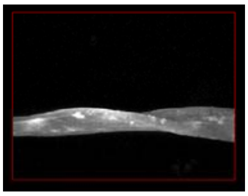


Image credit: (Sibarita, 2005)

- 2D image acquired, then objective is moved slightly
- Repeat until desired sample thickness is covered

Confocal microscopy



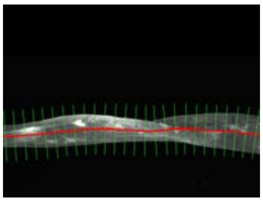


Cotton fiber imaging

- Fibers are vapor fixed with acrolein to produce high autofluorescence
- Imaging complete fiber takes several hours
- Produces 100-300 image volumes (depending on length of the fiber) of segments 100-150µm in length
- 100x magnification
- Resolution: 280nm/pixel in each dimension

Processing image volumes

Extract cross section volumes



- 2D maximum intensity projection used as a guide
- Medial axis identified using a series of morphological operations
- From each point along the medial axis, perpendicular profiles are extracted from each slice, i.e. a virtual cross section
- Cross sections are "stacked" to form a new image volume
- Cross section volumes effectively cut out most of the background

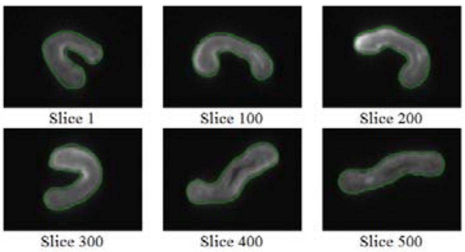
Processing image volumes

Segmentation of volumes

- Cross sections change very little from slice to slice
- Strategy: use previous segmentation result as initialization for the next slice; manually segment first slice to "prime the pump"
- Use level sets (Osher 1988) and Gradient Vector Flow (Xu and Prince 1997; Paragios et al. 2004) to evolve boundary

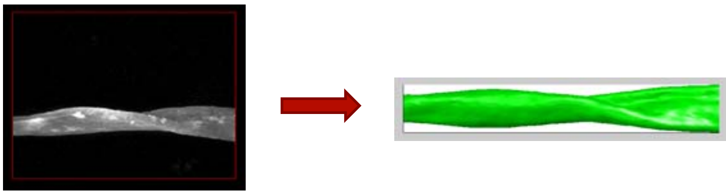
Level set equation:

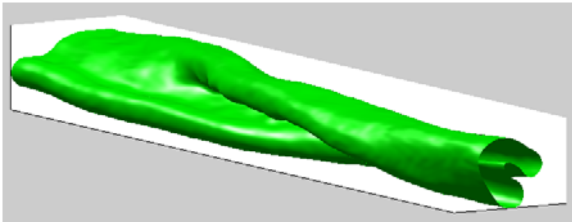
$$\Phi_t + \underbrace{\vec{V}\cdot\nabla\Phi}_{\text{external velocity force}} + \underbrace{\beta f_n|\nabla\Phi|}_{\text{normal force}} = \underbrace{\kappa f_c \nabla^2\Phi}_{\text{curvature force}}$$



Processing image volumes

3D Reconstruction using segmented slices





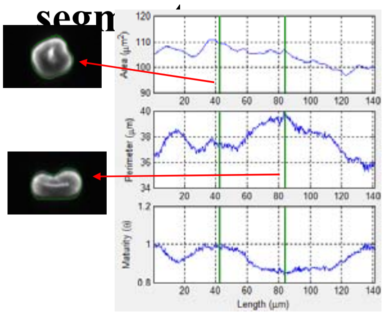
Cross section measurements

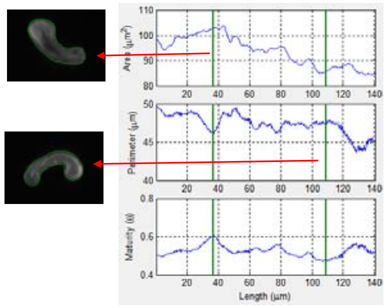
Cross section reference method applied

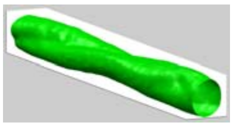
- Given the known boundaries of a cross section, we can apply the reference method measurements directly
- Area is the sum of the pixels inside the boundary
- Perimeter calculated along the boundary using the Digital Straight Segments algorithm (Kovalevsky, 1989; Kovalevsky and Fuchs, 1992)

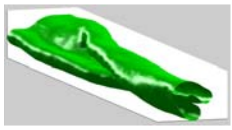
Results

Average maturity fiber – highlighted segn









Conclusion

Maturity can vary significantly

- **Visual observation as well as quantitative measurements confirm that maturity can vary significantly within a single fiber**
- **Average maturity (θ) fiber varied over the length of the fiber from 0.4 to 1**
  - ***Similar intra-fiber variation was reported by (Shahriar 2012)***

General Conclusion

- Genetic variability of within-plant variability do exist.
- Variability within-plant of fiber length distributions appear to have an impact on yarn tenacity.
- Understanding individual fiber tensile properties distributions and their impact on yarn quality is essential.
- Propensity to break a cotton fiber is likely related to fiber maturity and variation of fiber maturity along the length (weak spots).

General Conclusion

- HVI cannot provide information about fiber properties distributions.

- AFIS or preferably an improved AFIS are essential to develop the germplasm of the future.

Acknowledgments

- Cotton Incorporated
- CSIRO

TEXAS TECH UNIVERSITY