Moldflow Summit 2017

Bend, Don't Break When Processing Long-Fiber Thermoplastic Resins

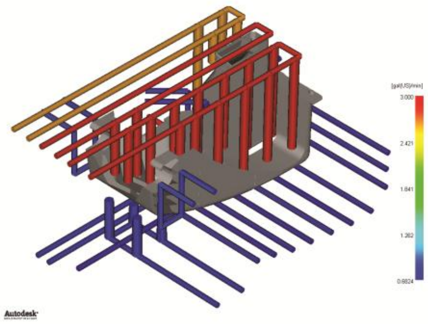
Erik Foltz, Max Zamzow, and Dayton Ramirez

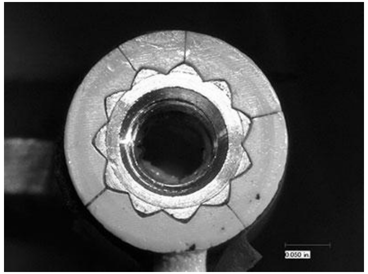
The Madison Group
www.madisongroup.com

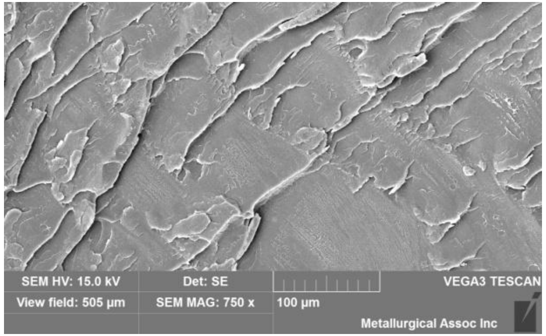
AUTODESK.

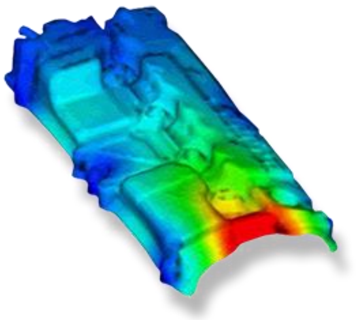
The Madison Group

- An Independent Plastic Consulting Firm
  - Founded in 1993
  - Located in Madison, WI
- Helping Clients Optimize the Performance of Their Part Designs









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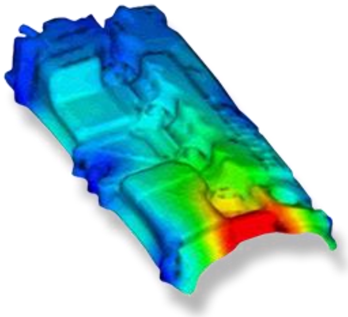
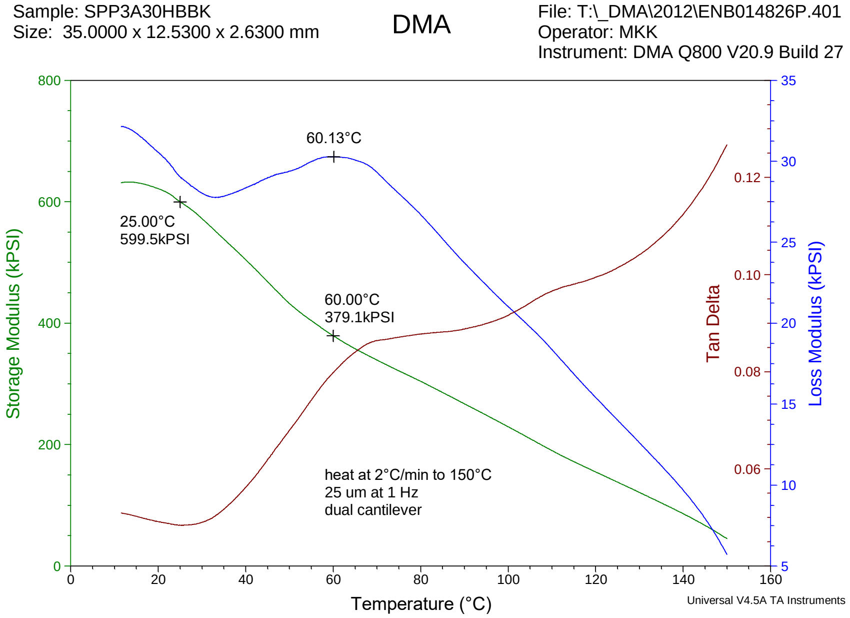
- Material Engineering
  - Material Selection
  - Product Design Evaluation
  - Structural FEA
  - Mechanical and Thermal Material Characterization
  - Aging and Compatibility
  - Product and Life Time Analysis





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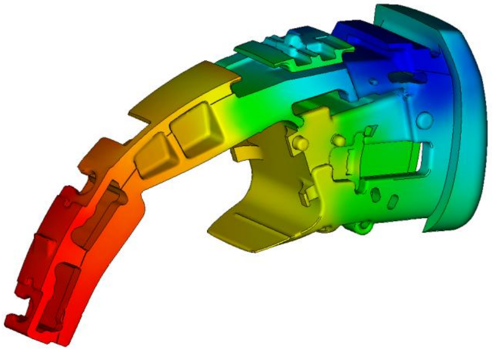
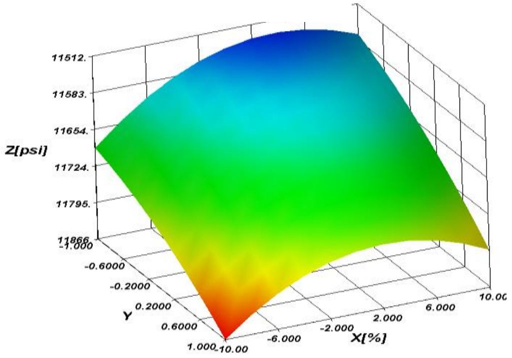
- Processing Analysis:
  - Moldflow Analysis
    - Injection Molding
    - Compression Molding
    - Thermoset and Thermoplastic
  - Physical DOE Set Up and Analysis
    - Process Capability
    - Product Qualification





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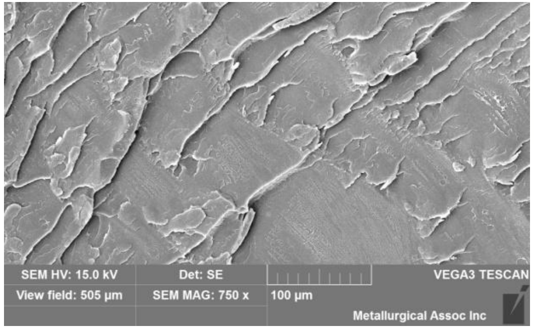
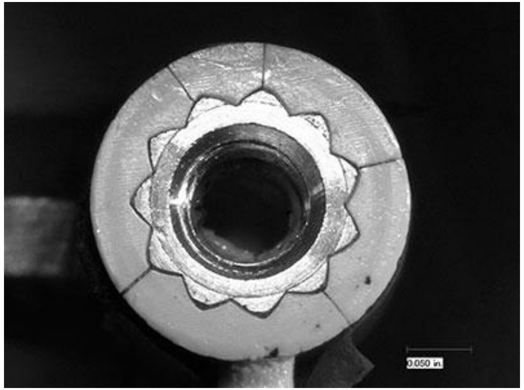
- Failure Analysis
  - Determination of Root Cause
  - Failure Type Assessment
  - Fractography
  - Destructive and Non-Destructive
  - On-site Support





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Long-Fiber Thermoplastics

Material Selection

- When Selecting Material Need to Consider:
  - Performance Requirements
    - (Lifetime, Temperature, Stresses, Strains)
  - Part Design
  - Environment
  - Cost

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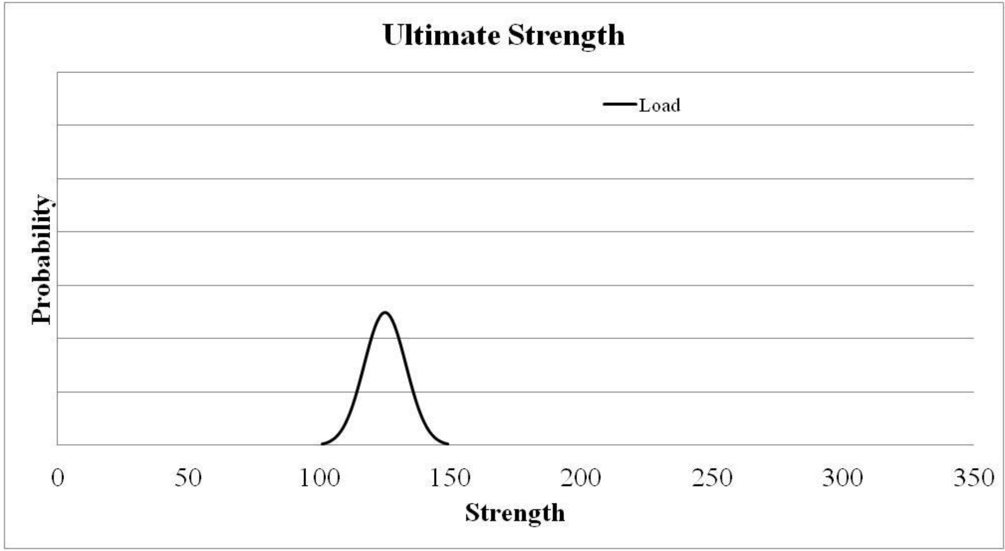
Metal to Plastic Conversion

- First Criteria of Material Selection is a Good Understanding of the Expected Performance Criteria of the Part



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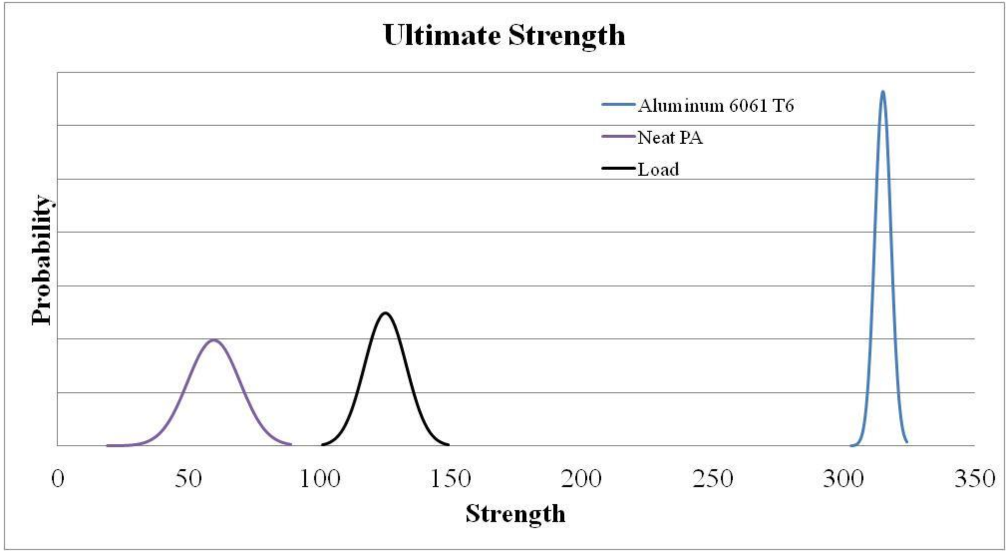
Material Selection

- Then it is Important to Understand Different Material Options



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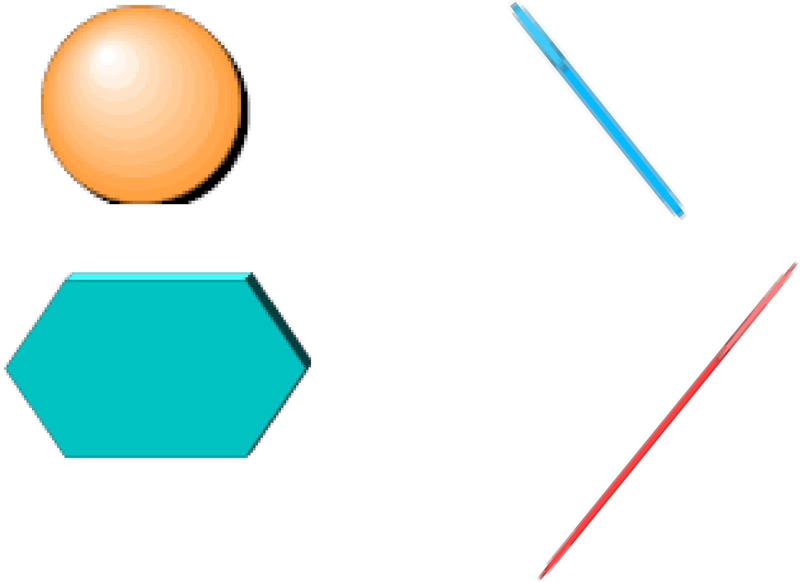
Material Additives

- Add Fillers to Improve the Properties of the Base Resin



Filler	A/R	Types
Sphere	1	Talc
Plate /Flake	20-200	Mineral
Needle	5-20	Milled Glass
Fiber	20-200+	Glass Fibers, Carbon Fibers, Long Fibers

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Metal to Plastic Conversion

- Improved Corrosion Resistance
- Ability to Net Form Final Shape
  - Part Consolidation
  - Eliminate Secondary Operations
- Reduced Part Weight and Cost

- Less Dimensional Stability
- Temperature Has Greater Role on Performance
- Need to Consider the Effects of Time
  - (Creep or Stress Relaxation)

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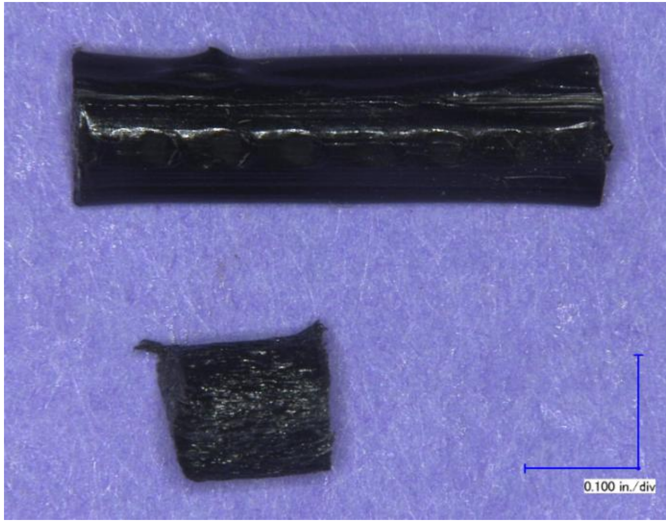
Long-Fiber Thermoplastic Composites

- Development of Discontinuous Fiber Reinforced Thermoplastic Composites Have Increased the Opportunity for Thermoplastic Resins
  - PP
  - PA6
  - PA66
  - TPU
- Introduction of Long Fibers Allows for Improvements of:
  - Young's Modulus
  - Tensile Strength
  - Impact Strength
  - Creep/ Fatigue Performance



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Long Fiber Thermoplastic Composites

- Examination of Datasheet Values Suggest that the Short-Term Performance of Long Glass Fiber Composites Approaches that of Traditional Materials

	Modulus	Ultimate Tensile Strength
6061 T6 Aluminum	68.9 GPa	310 MPa
60% Long Glass Fiber PA66	21.37 GPa	262 MPa

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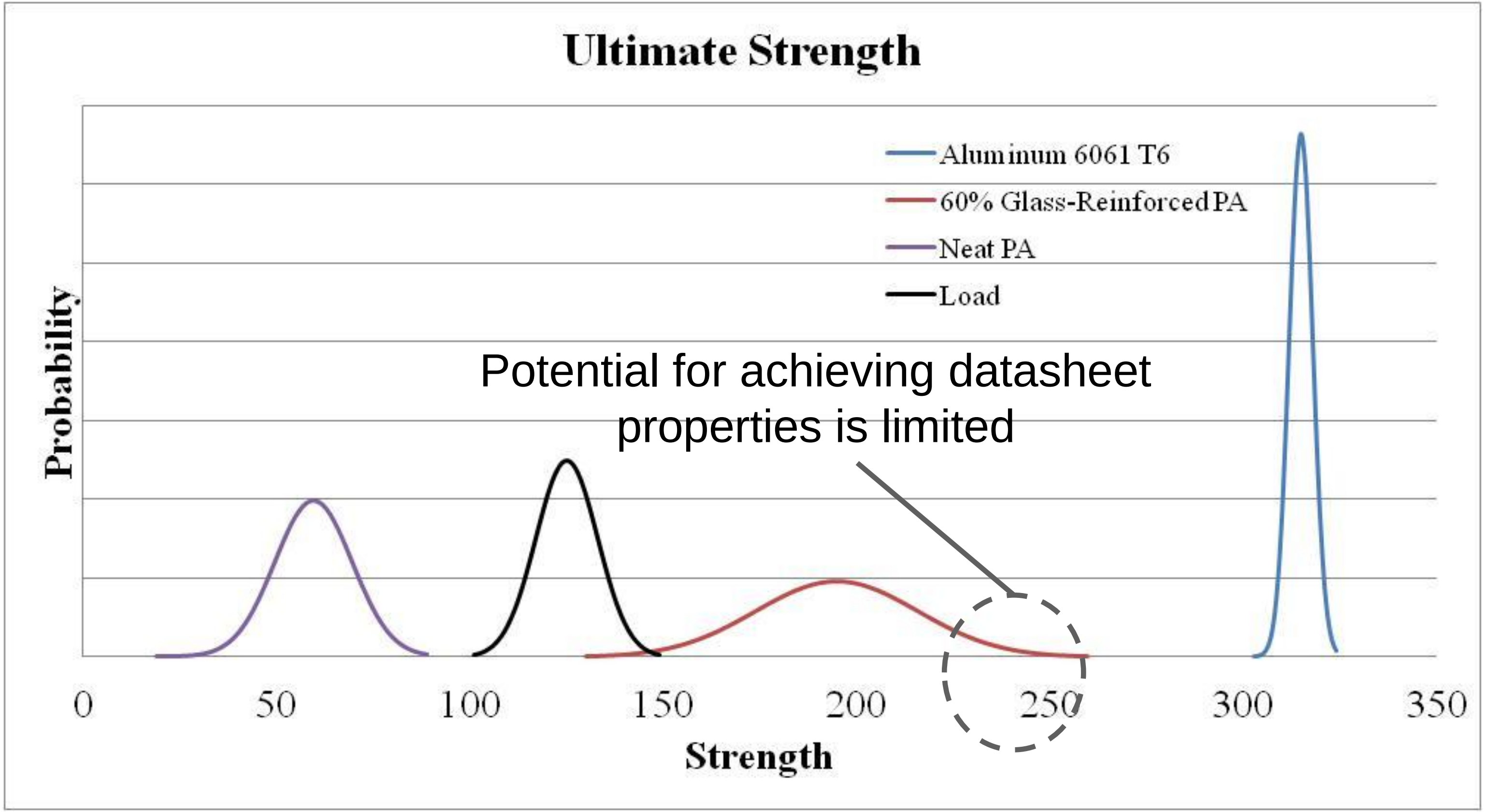
Potential of Achieving Datasheet Values



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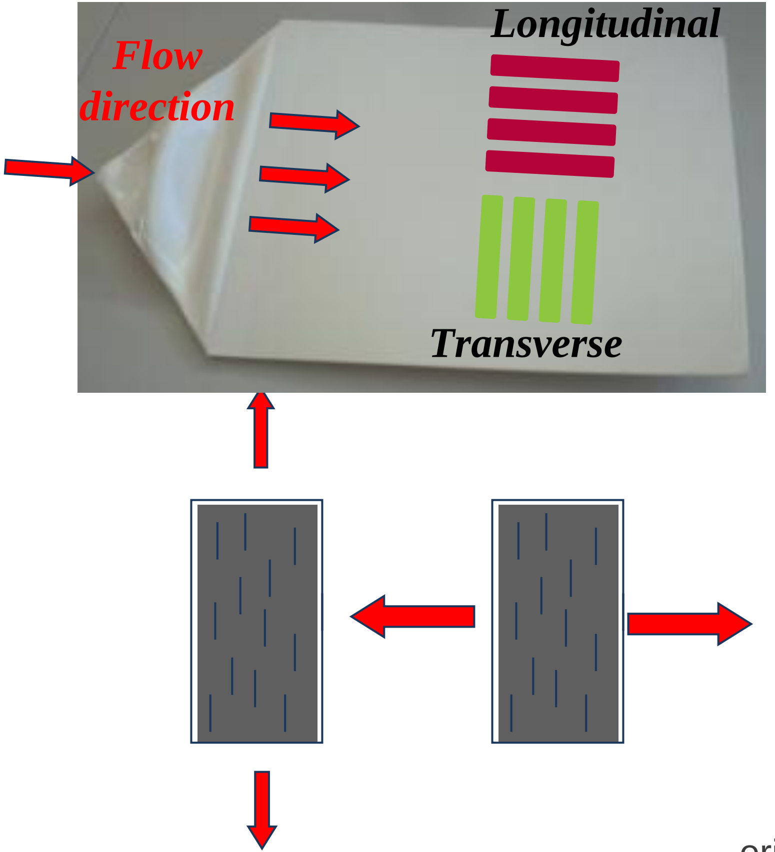
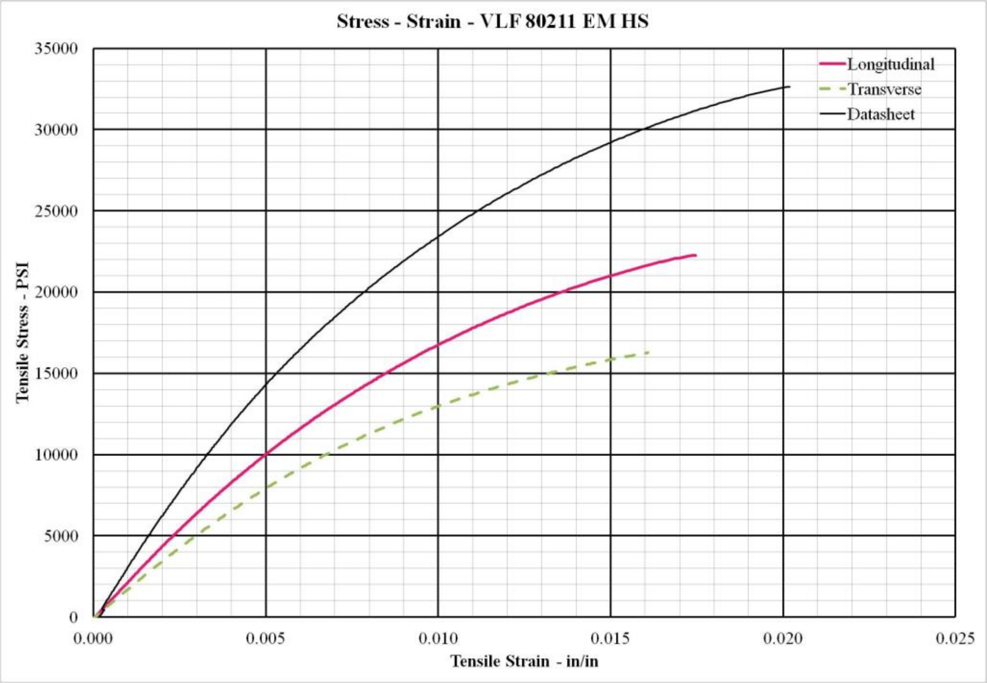
Role of Fiber Orientation on Performance





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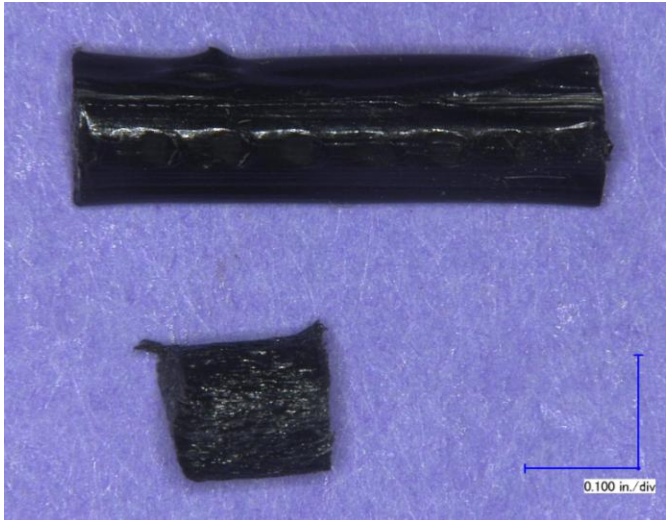
Role of Fiber Length on Performance

- In addition to the Orientation of the Fibers in Molded Part, the Length of the Fibers Also Influences the Performance of the Molded Part
  - Short Fiber – 300 -1000 µm
  - Long Fiber – 1 mm – 50 mm
- Fiber Length has a Significant Influence on:
  - Impact Strength
  - Young's Modulus
  - Tensile Strength



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Role of Fiber Length on Performance

Matrix	Glass Fiber (Weight %)	Specific Gravity	Tensile Strength (10^3 psi)	Tensile Modulus (10^6 psi)	Flexural Modulus (10^6 psi)	Impact Strength (ft. lb/in)
Polyester SMC (Compression Molded)	30	1.85	12.0	1.70	1.60	16.0
Polyester BMC (Compression Molded)	22	1.82	6.0	1.75	1.58	4.3
Nylon 6 (Injection Molded)	30	1.37	23.0	1.05	1.20	2.3
Polyester (PBT) (Injection Molded)	30	1.52	19.0	1.20	1.40	1.8

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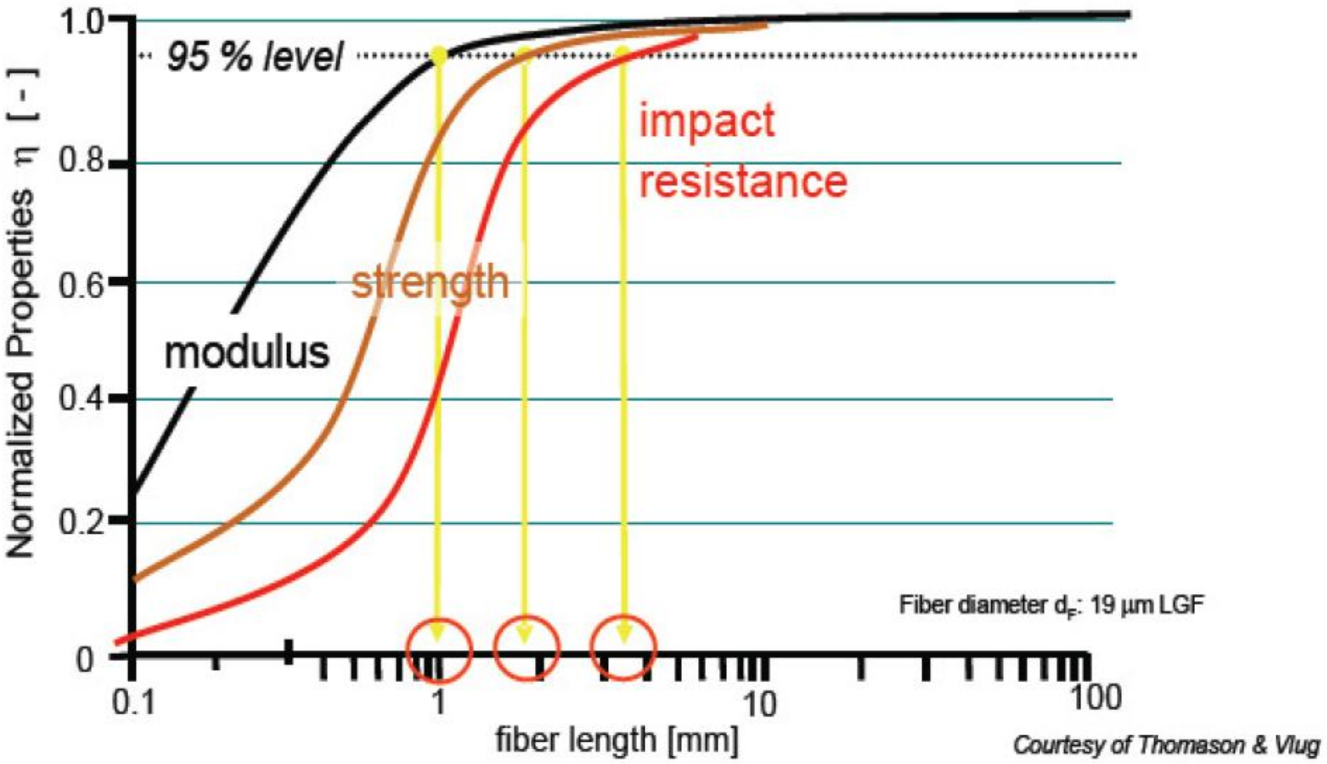
Role of Fiber Length on Performance



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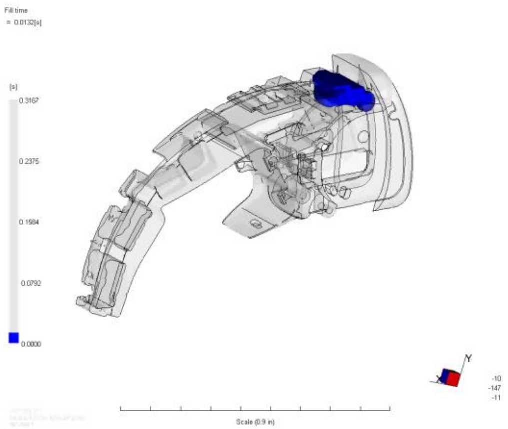
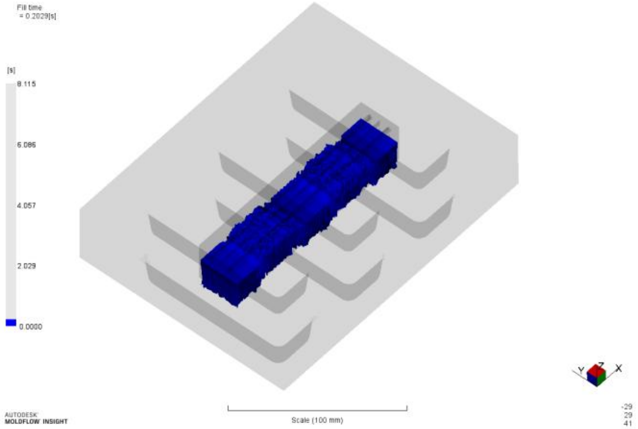
Long-Fiber Thermoplastic Processing

- Another Advantage of Long-Fiber Thermoplastic Resins is the Use of Traditional Manufacturing Methods to Mass Produce Components
  - Extrusion (1- 20 mm Long Fibers)
  - Injection Molding (1- 12 mm Long Fibers)
  - Compression Molding (12 mm to 50 mm Long Fibers)





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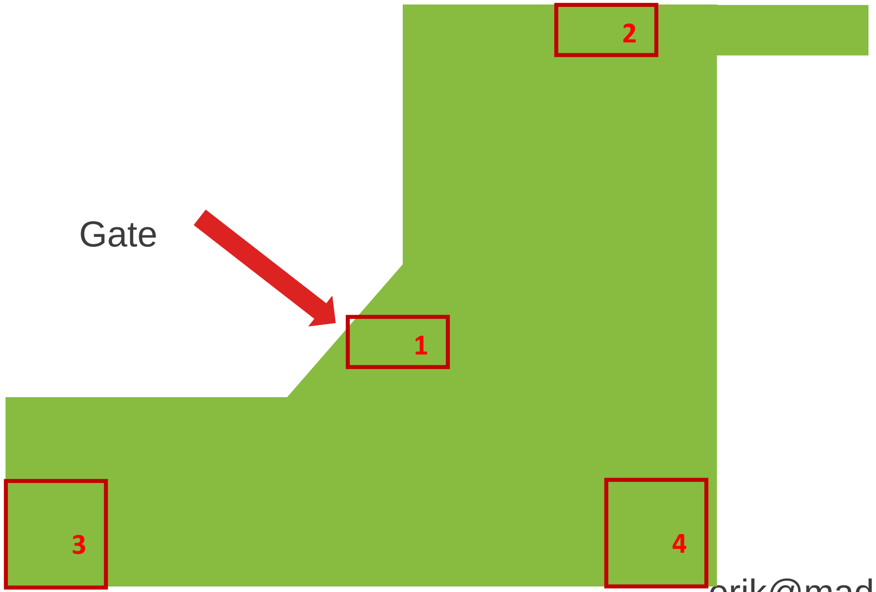
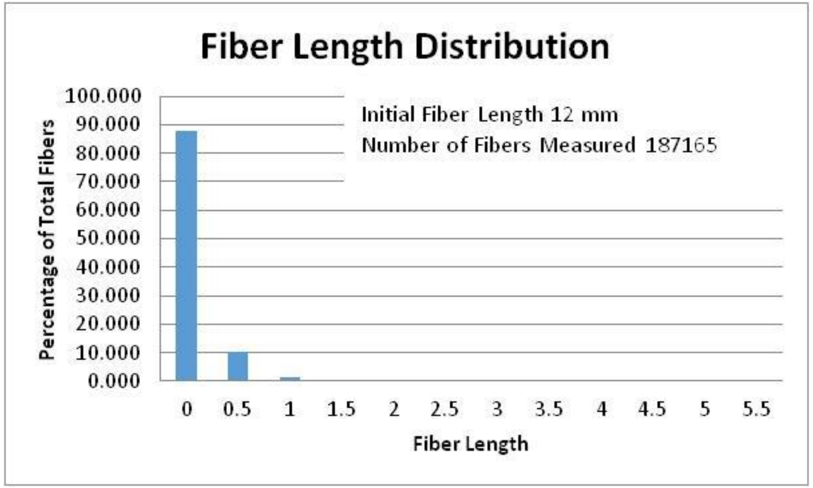
Final Fiber Length Distribution In Part

- Fiber Length in Molded Part is Substantially Shorter





Sample Location	Number Average Fiber Length L_n [mm]
Location 1	0.322
Location 3	0.299
Location 4	0.340

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Critical Fiber Length

- In Order to Benefit from the Incorporation of Discontinuous Fibers, a Critical Length Must Be Attained
  - Otherwise Fibers Act as Inclusion and Stress Concentrators
- Based on Several Factors
  - Polymer Matrix
  - Fiber Sizing
  - Type of Fiber
- Critical Fiber Length for PP is:
  - 1.3 mm for Uncoupled
  - 0.9 mm for Chemically Coupled

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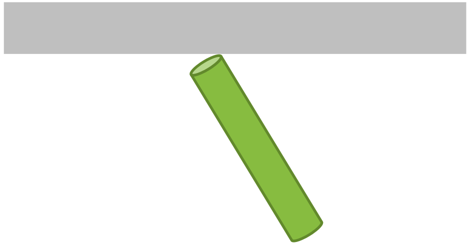
Fiber Breakage

Fiber Breakage Sources

- Three Primary Sources for Fiber Breakage During Injection Molding
  - Fiber – Fiber Interaction
  - Fiber – Wall Interaction
  - Fiber – Matrix Interaction



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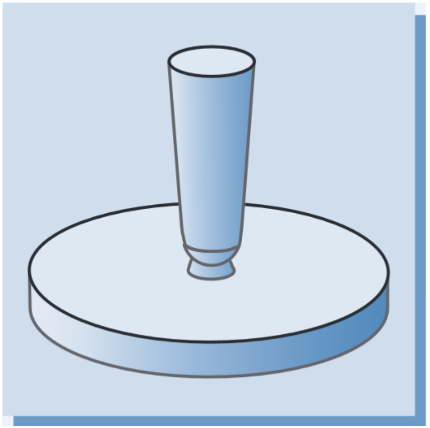
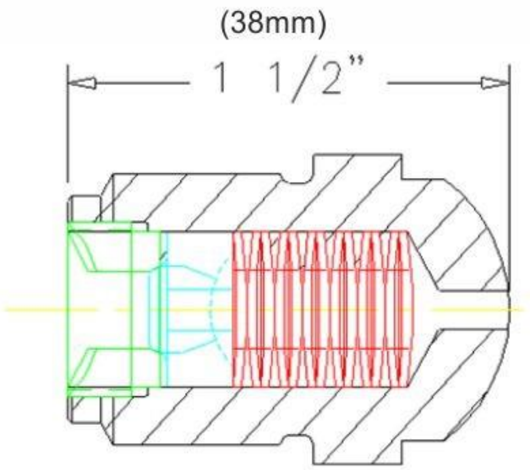
Fiber Breakage Sources

- These Conditions Are Most Predominant When There are Contractions in Flow





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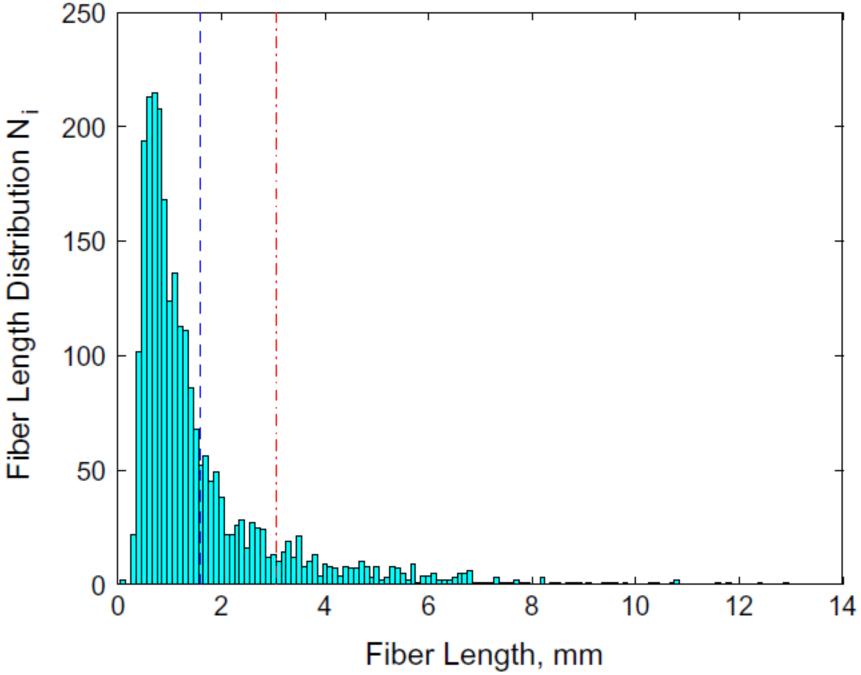
Fiber Length Distribution In Molded Part

- Fiber Length Distribution in Molded Part is Representative of a Weibull Distribution with a Bias Toward Shorter Fibers
  - Initial Fiber Length – 12 mm



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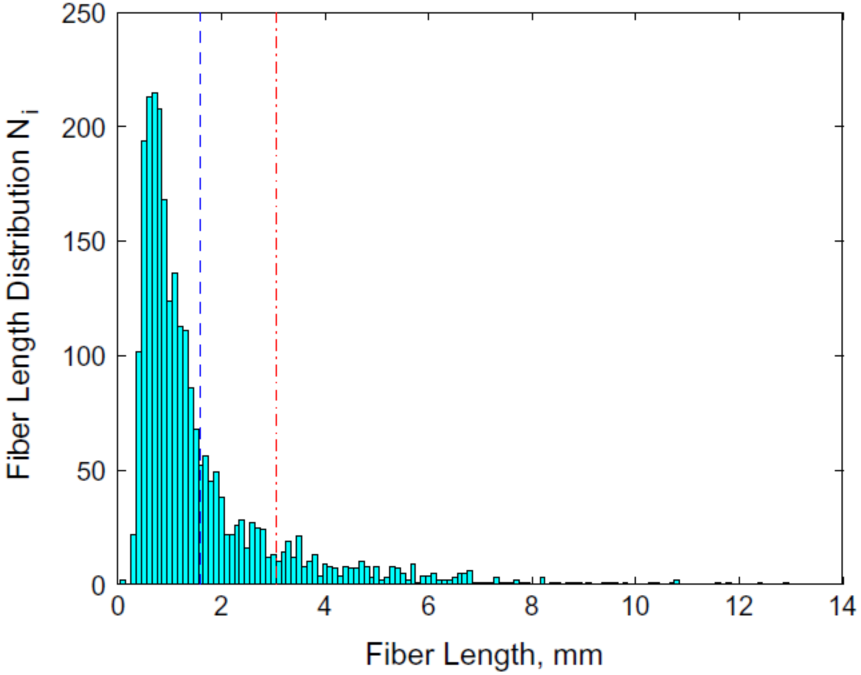
Fiber Length Distribution Nomenclature

- Two Predominate Ways of Describing Length of Fibers In Final Molded Part
  - Number Average – Average Length Based on Number of Fibers
  - Weight Average – Average Length Based on Total Weight

$$\overline{L_n} = \frac{\sum N_t l_t}{\sum N_t} \qquad \overline{L_W} = \frac{\sum N_t l_t^2}{\sum N_t l_t}$$

$$N_t = Number\ of\ fibers\ at\ time\ t$$

$$l_t = Length\ of\ fibers\ at\ time\ t$$



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Fiber Length Distribution Nomenclature

- Number averaged length ≤ weight averaged length

$$\overline{L_n} = \frac{\sum N_t l_t}{\sum N_t} \qquad \overline{L_W} = \frac{\sum N_t l_t^2}{\sum N_t l_t}$$

$$N_t = Number\ of\ fibers\ at\ time\ t$$

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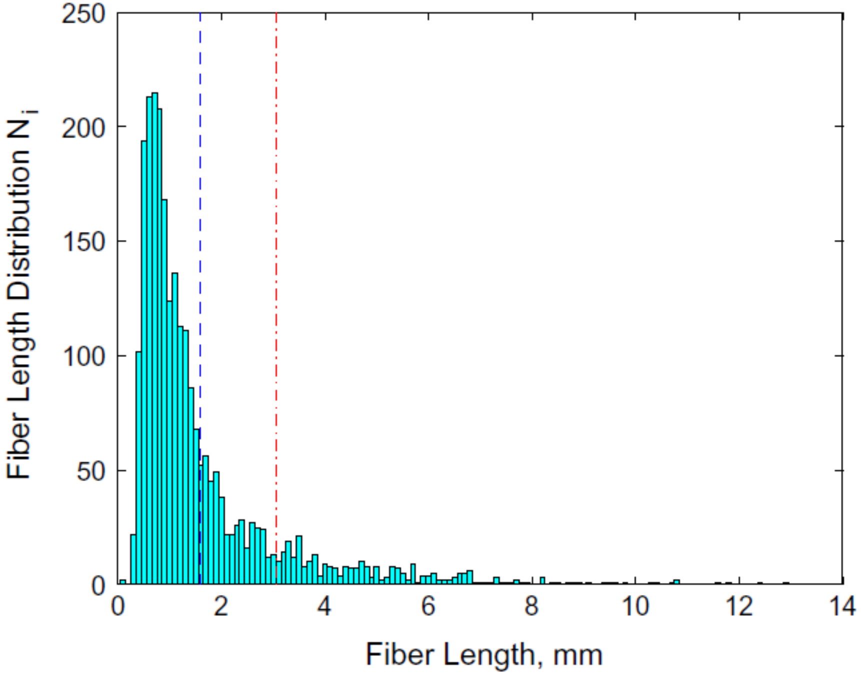

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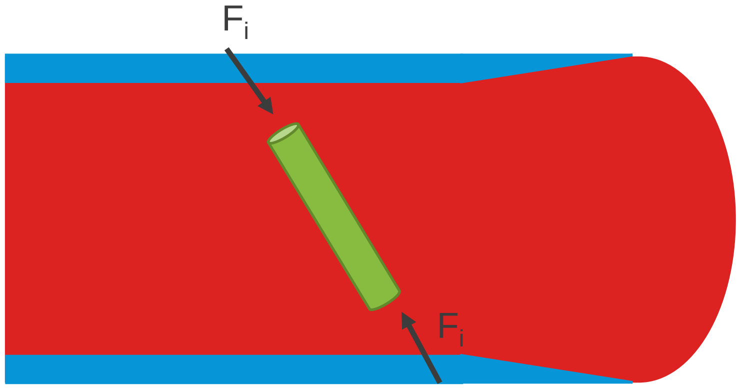
Fiber Breakage Model

Fiber Breakage Model

- Autodesk Moldflow Implemented Fiber Breakage Model Based on Hydrodynamic Loading of Fiber (Fiber Matrix Interaction)
- Fiber Break Due to Buckling Load From Differences in Velocity



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Fiber Breakage Model: Critical Load

- Fibers Will Break When Hydrodynamic Forces Exceed Critical Buckling Force
  - Based on Eulerian Buckling Conditions

$$\frac{F_i}{F_{crit}} = \frac{8\zeta\eta_m l_i^4}{\pi^3 E_f d_f^4}(-\widehat{D}:\hat{A})$$

F_i = *Hydrodynamic Compression Force*

F_{crit} = *Critical Buckling Force*

ζ = *Drag Factor*

η_m = *Viscosity*

l_i = *Fiber Length*

E_f = *Fiber Elastic Modulus*

d_f = *Fiber Diameter*

$\widehat{D}$ = *Deformation Rate Tensor*

$\hat{A}$ = *Fiber Orientation Tensor*

http://help.autodesk.com/view/MFIA/2017/ENU/?guid=GUID-4FBB0674-91DE-415D-AE64-D230656C98AB

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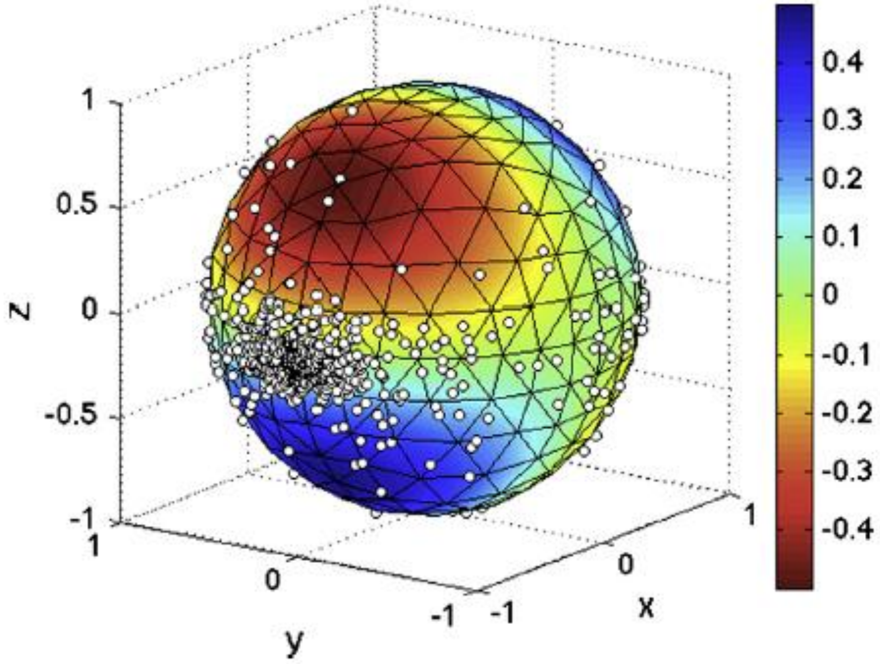
Fiber Breakage Model

- Therefore, Fiber Breakage Is Dependent on Aligning the Orientation of the Fibers With Critical Hydrodynamic Forces
- Need Probability Equations for When Critical Loading Condition and Fiber Orientation Coincide



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Fiber Breakage Model: Probability Function

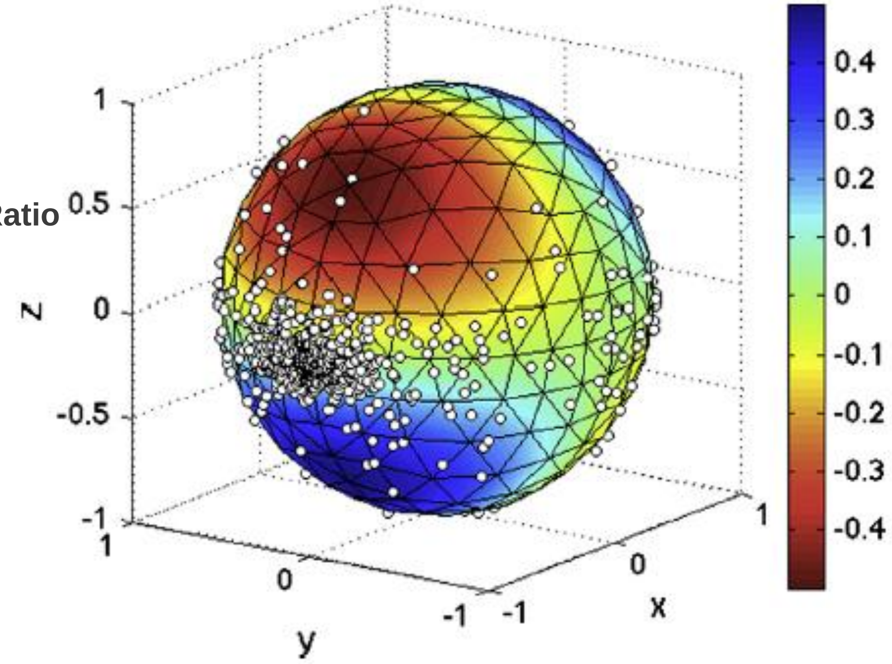
- For a Single Fiber, the Probability of Breaking Under the Hydrodynamic Forces can be Expressed as:

Hydrodynamic Force Ratio

Shear Rate Constant

$$P_i = C_b \dot{\gamma} max\left\{0, \left[1 - exp\left(1 - \frac{F_i}{F_{crit}}\right)\right]\right\}$$

Maximum Shear Rate



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Fiber Breakage Model: Child Fiber Generation

- *L* = Initial fiber length
- *N(l,t)* = Number of fibers with length *l* at time *t*
- *P(l)* = Scalar probability function of fiber length *l*
- *R(l,l')* = Probability function of fiber length and fiber breakage to form a fiber length *l'* (where *l'<l*)

$$\frac{dN(l,t)}{dt} = -P(l)N(l,t) + \int_l^L R(l,l')N(l',t)\,dl'$$

Loss of fibers by breaking

Gain of fibers due to breakage at *l'*

***Can be expressed as a Gaussian breakage profile**

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Fiber Breakage Model: Child Fiber Generation

- Probability of the Breaking Fiber to Break into Different Length Child Fibers
- Assumes Highest Probability Will Result in Fiber Breaking in Half

$$R(l,l') = G_{norm}\left(l, \frac{l'}{2}, Sl'\right)$$

$l \quad = Variable\ (Fiber\ Length)$

$\frac{l'}{2} \quad = Mean$

$Sl' = Standard\ Deviation$

$S \quad = Scaling\ Factor$

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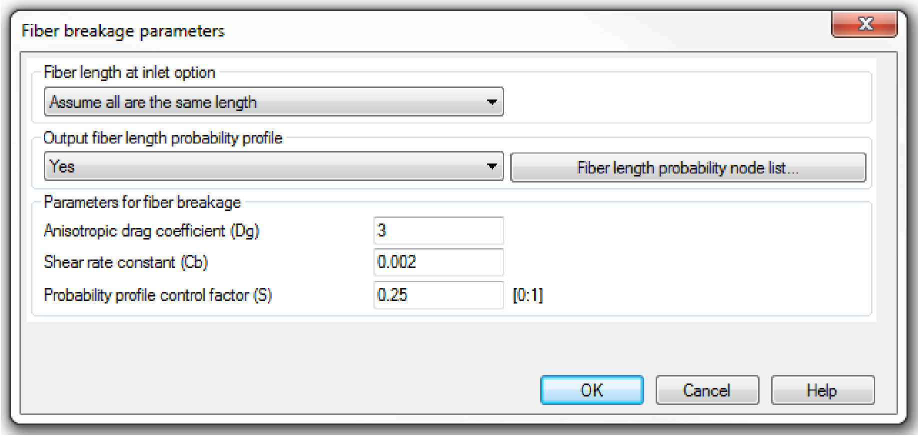
Fiber Breakage Model: Model Parameters

- Model Consists of Three Parameters:
  - ζ Influences Minimum Fiber Length for Breakage
  - C_b Controls the Probability of Fiber Breakage
  - S Controls How the Parent Fiber Breaks into Children Fibers
- Additionally, User Can Provide Fiber Length Distribution at the Inlet Location



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Fiber Breakage Model: Parameters

- ζ Influences Minimum Fiber Length for Breakage
- C_b Controls the Probability of Fiber Breakage
- S Controls How the Parent Fiber Breaks into Children Fibers

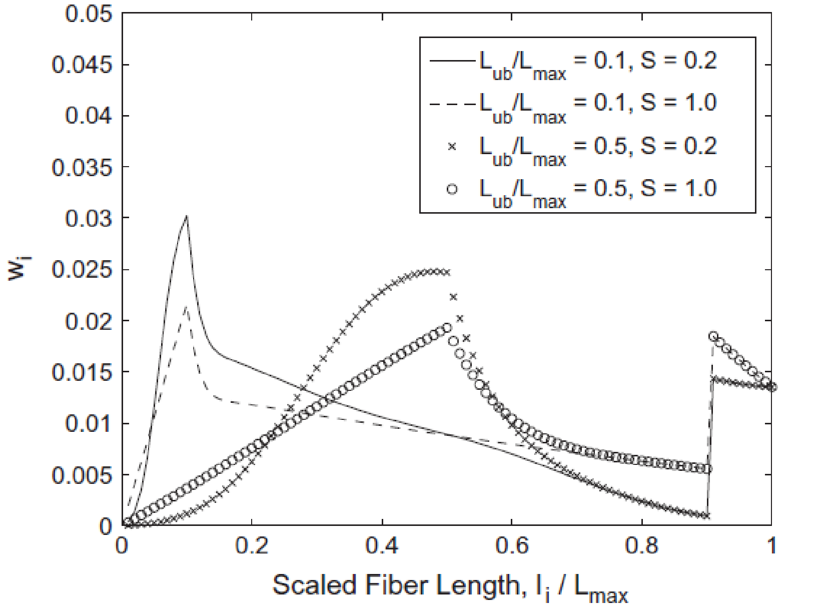

Fig. 5. Weight-based fiber length distributions at intermediate time, $t^* = 2$, for different values of the model parameters S and L_{ub} in steady simple shear flow. ($t^* \equiv C_B \dot{\gamma} t$).

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Fiber Breakage Model: Parameters

- ζ Influences Minimum Fiber Length for Breakage
- C_b Controls the Probability of Fiber Breakage
  - Also Time to Reach Steady Stat
- S Controls How the Parent Fiber Breaks into Children Fibers

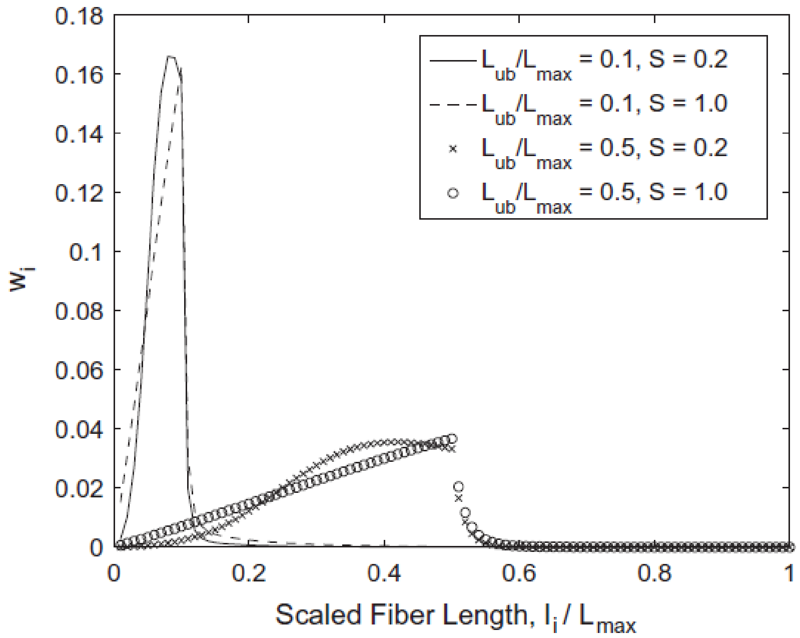

Fig. 6. Weight-based fiber length distributions at long time, $t^* = 10$, for different values of the model parameters S and L_{ub} in steady simple shear flow. ($t^* \equiv C_B\dot{\gamma}t$).

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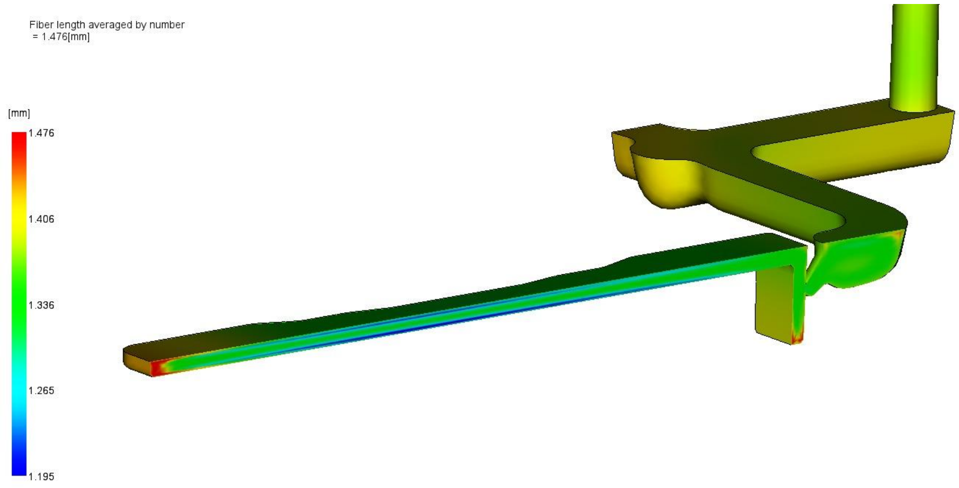
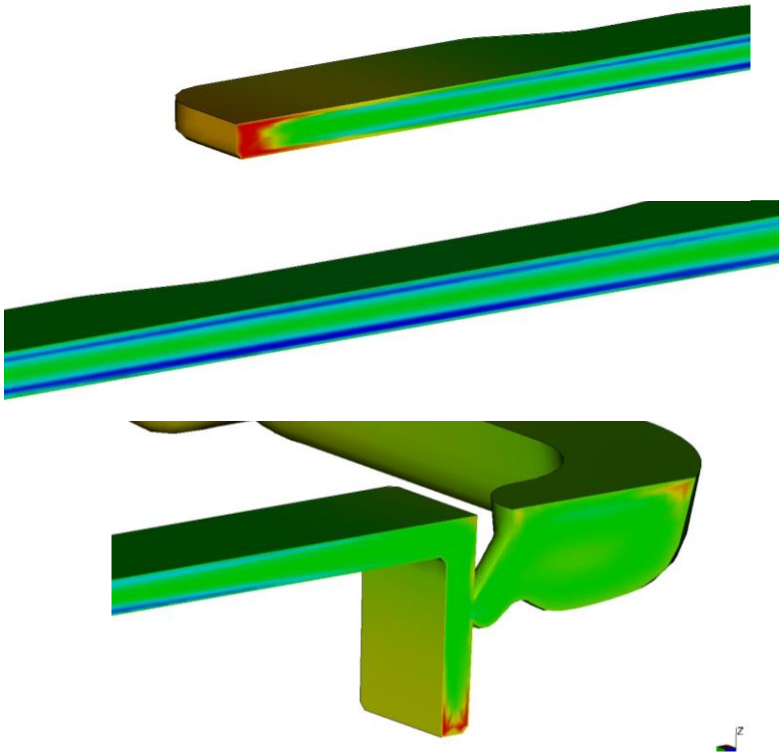
Fiber Breakage Model: Results

- Simulation Can Provide Information on:
  - Number Average or Weight Average Fiber Length





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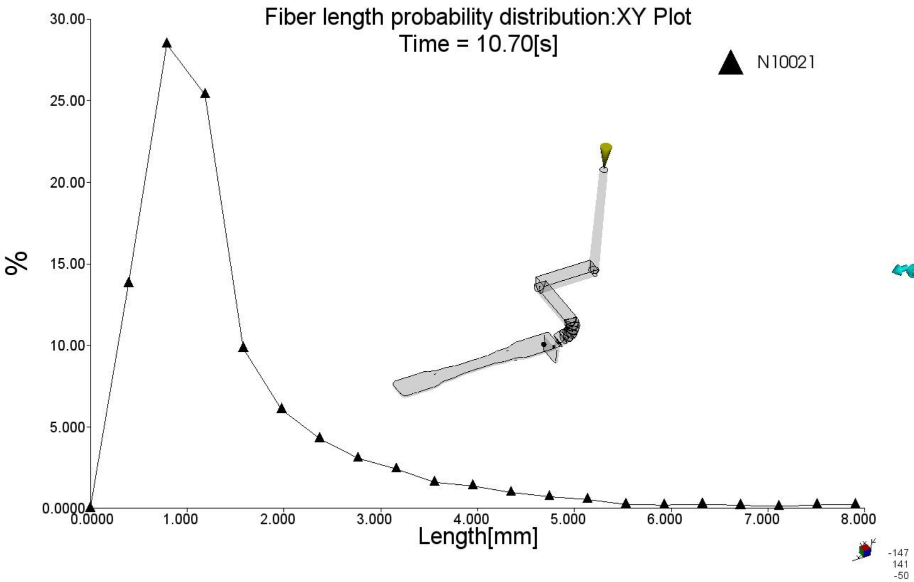
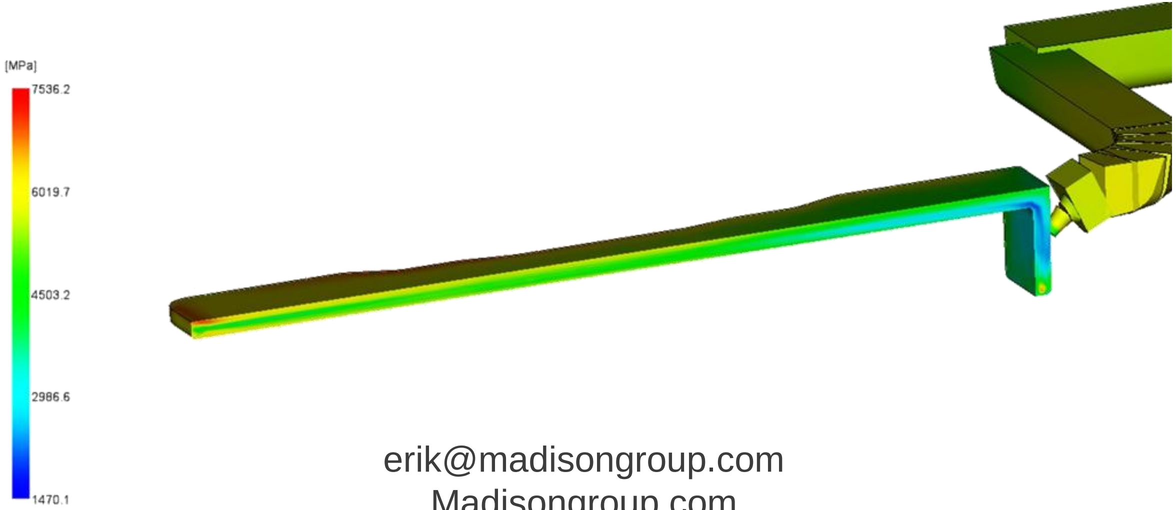
Fiber Breakage Model: Results

- Simulation Can Provide Information on:
  - Number Average or Weight Average Fiber Length
  - Fiber Length Probability Distribution



Fiber Breakage Model: Results

- Simulation Can Provide Information on:
  - Number Average or Weight Average Fiber Length
  - Fiber Length Probability Distribution
  - Linear Elastic Composite Properties



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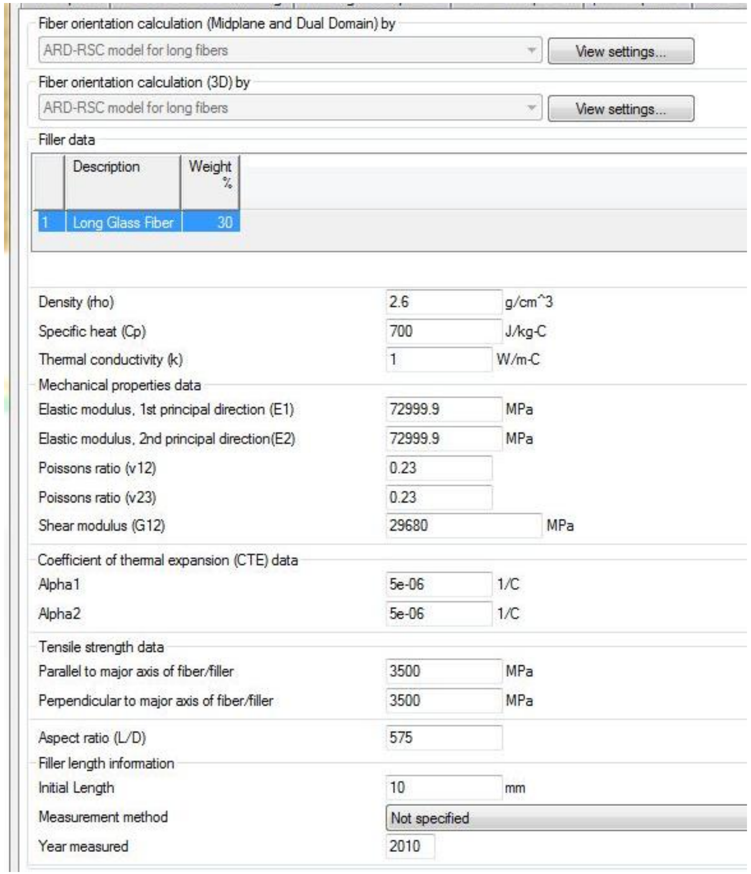
Fiber Properties

- Simulation Can Provide Information on:
  - Number Average or Weight Average Fiber Length
  - Fiber Length Probability Distribution
  - Linear Elastic Composite Properties
- In order to Get Good Mechanical Characterization, Need to Have Good Filler Characterization
  - Also, Need to Obtain Good Fiber Orientation



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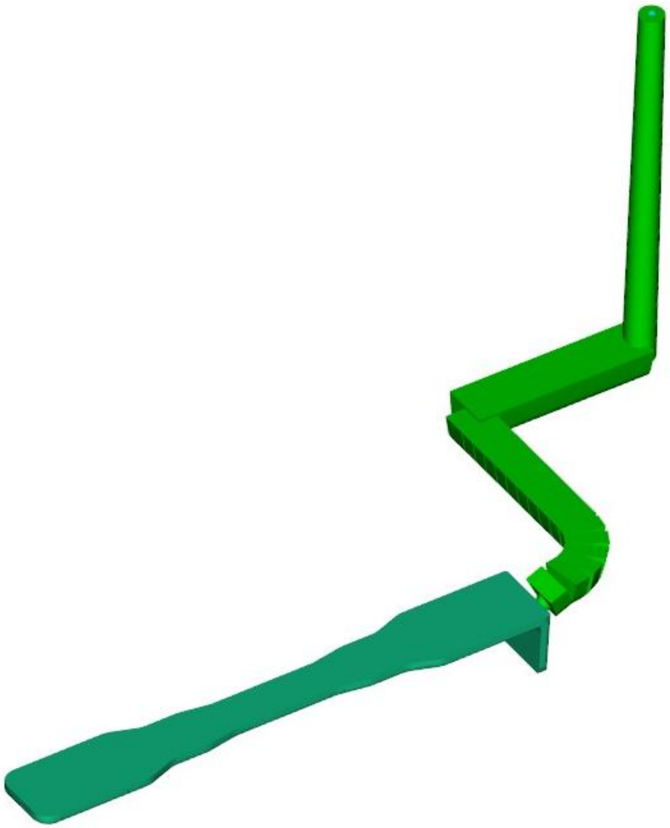
Fiber Breakage Correlation

Fiber Breakage Study

- Goal: Correlate the Fiber Length Model to Molded Parts
- Geometry: Modified Tensile Bar
- Material: 30%wt Chemically Coupled Long Glass-Reinforced PP
  - Initial Fiber Length 10 mm
- Injection Molded
  - Tunnel Gate into End of Bar
  - Varied Gate Size and Fill Time



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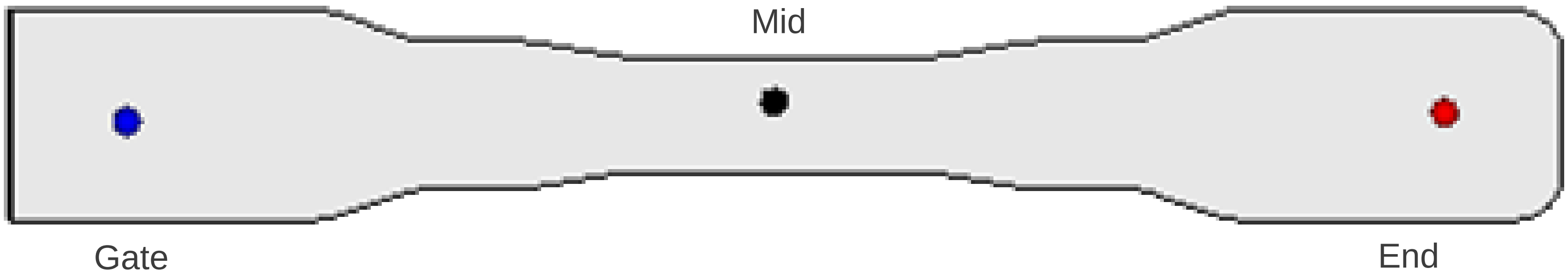
Fiber Breakage Study

- Performed Correlation Studies at Three Locations per Bar



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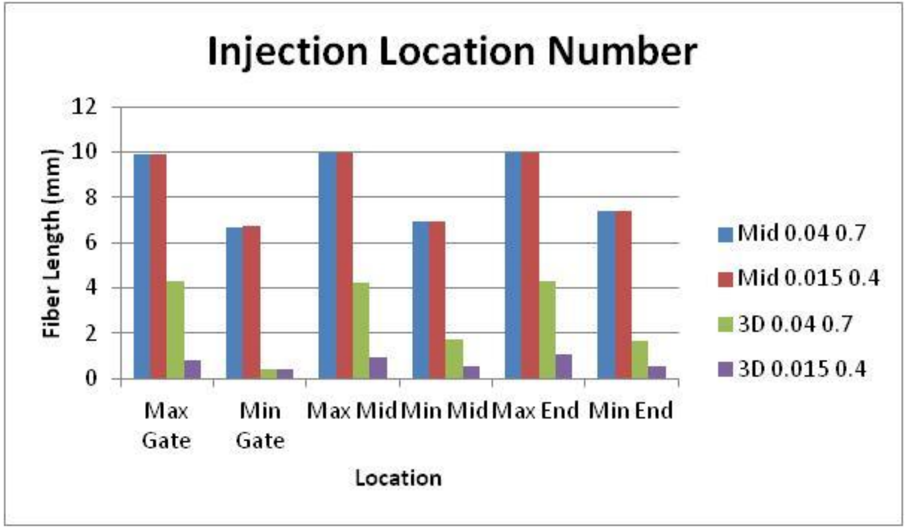
Madisongroup.com

Fiber Breakage Study

- Performed Baseline Analyses
  - Assumed all Fibers were 10 mm in Length
  - Ran Simulations with:
    - Midplane and Full 3D
    - Beam Elements for Runners
- Fill Parameters:
  - Gate Size 0.040” and 0.70 second Fill Time
  - Gate Size 0.015” and 0.40 second Fill Time



Fiber Breakage Study

Solver	Gate	Fill Time	Gate (Number Average)	Middle (Number Average)	End (Number Average)
Midplane	0.040”	0.70 second	6.73	6.98	7.63
Midplane	0.015”	0.40 second	6.68	6.91	7.42
3D	0.040”	0.70 second	0.78	1.24	1.29
3D	0.015”	0.40 second	0.78	0.91	0.93

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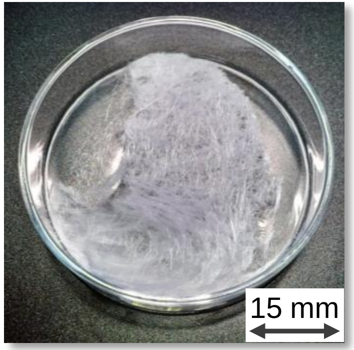
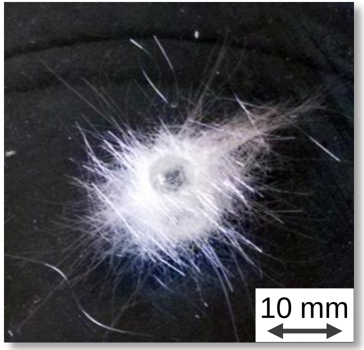
Fiber Measurement

Fiber Measurement

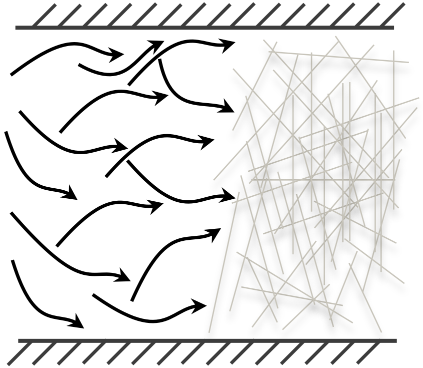
1. Sample Preparation



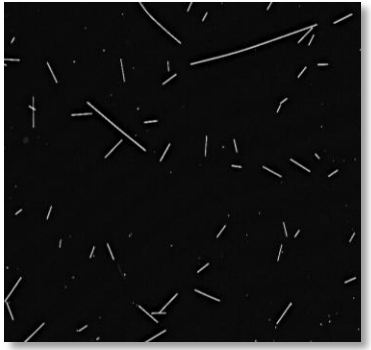
Matrix Removal



Down-Sampling



Fiber Dispersion



Digital Image

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Fiber Measurement

2. Image Processing

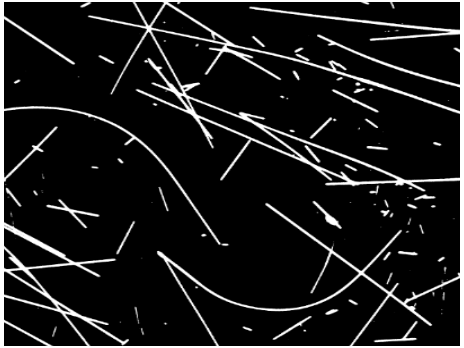
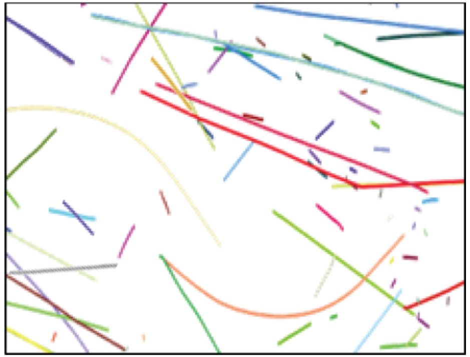
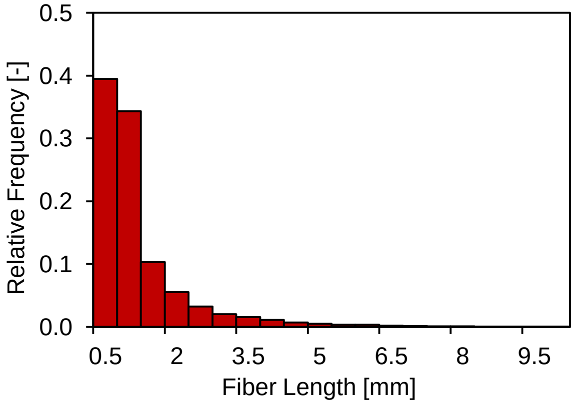


Image Enhancement and Thresholding



Automatic Fiber Detection



Data Analysis

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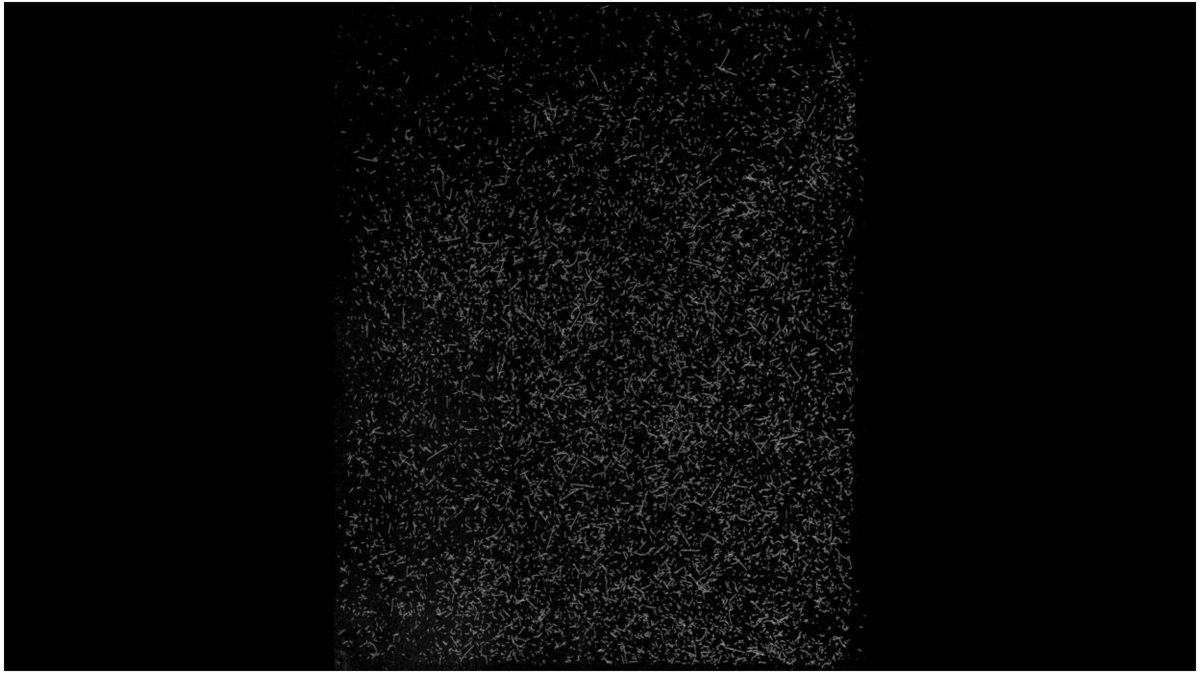
Fiber Measurement

- Illustration of dispersed fibers (approx. 7,500 fibers per scanned image)



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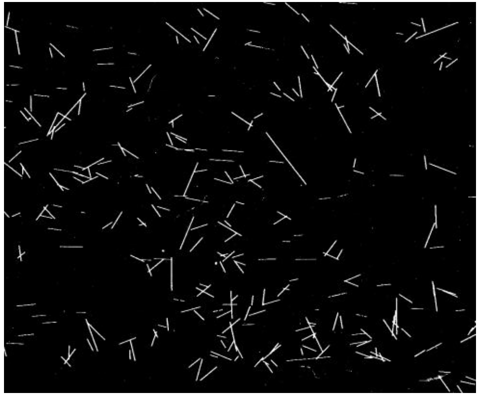
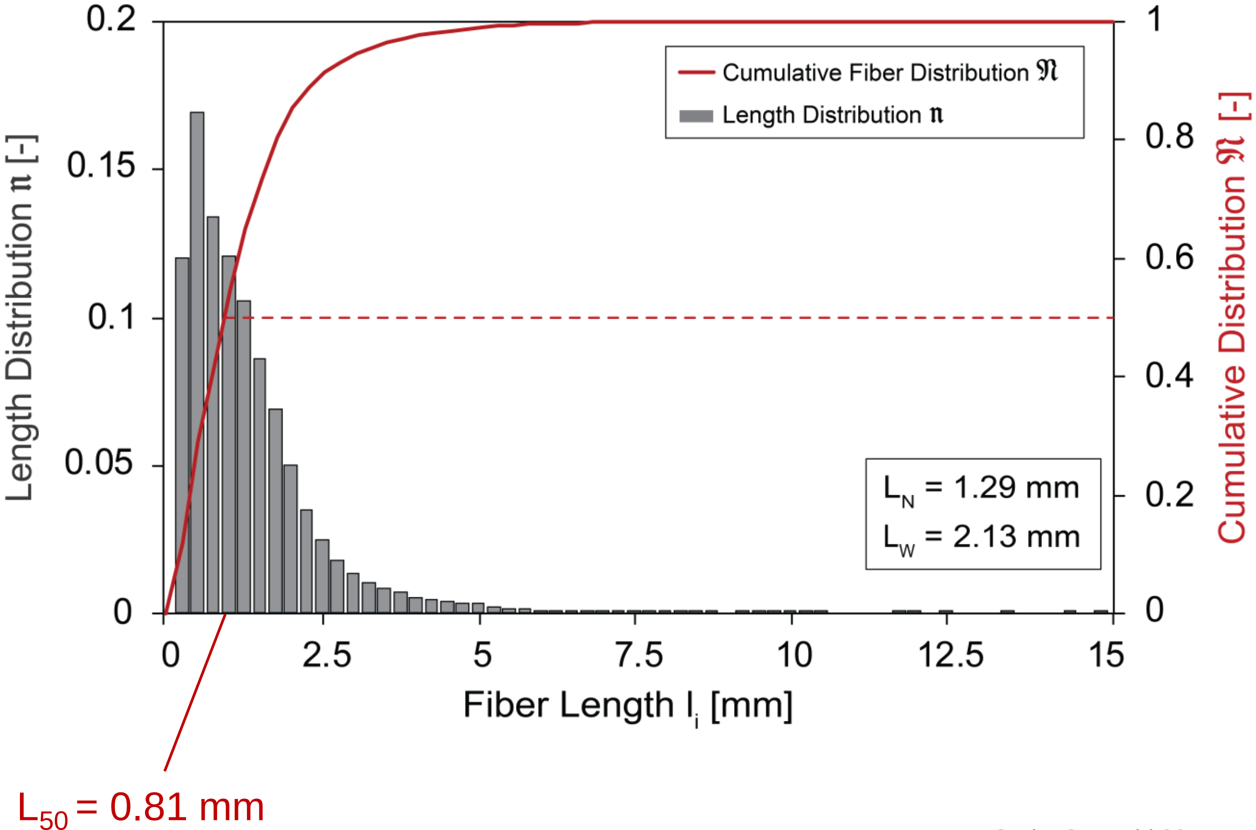
Fiber Measurement





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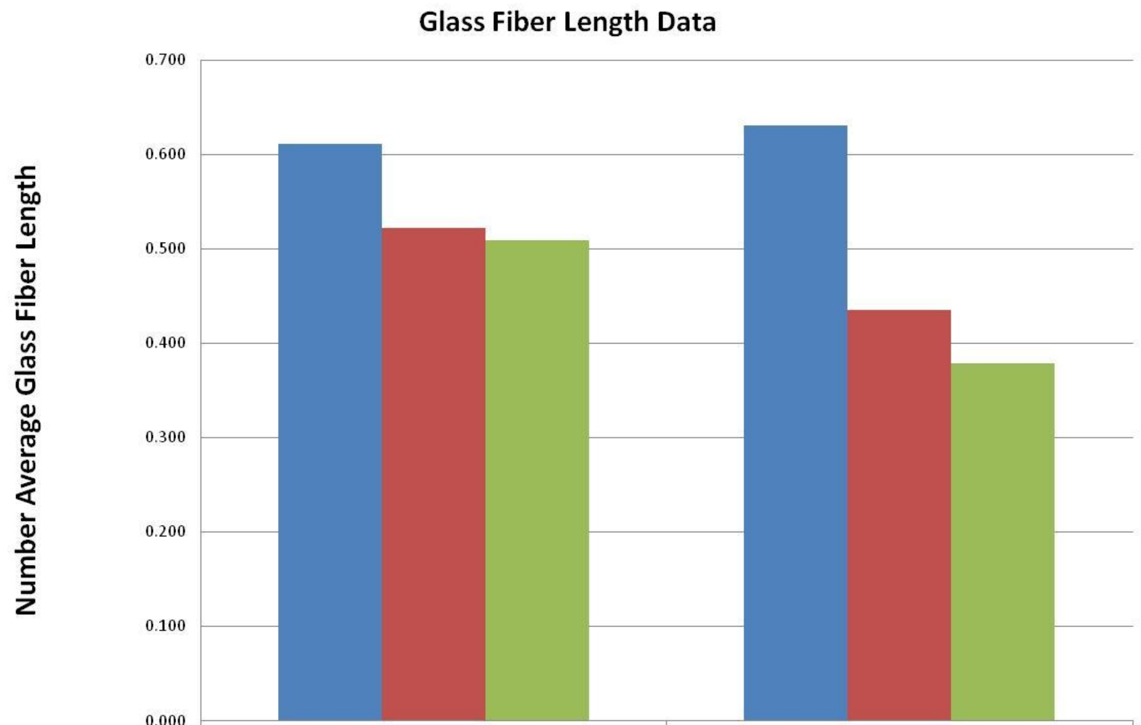
Correlation Study: Results



	0.04 Inch 0.7 Sec	0.015 Inch 0.4 Sec
LG Sprue Length (mm)	0.611	0.630
LG Gate Length (mm)	0.522	0.435
LG Middle Length (mm)	0.509	0.378

erik@madisongroup.com
Madisongroup.com

Fiber Breakage Study: Measurements

Solver	Gate	Fill Time	Gate (Number Average)	Middle (Number Average)	End (Number Average)
Midplane	0.040”	0.70 second	6.73	6.98	7.63
Midplane	0.015”	0.40 second	6.68	6.91	7.42
3D	0.040”	0.70 second	0.78	1.24	1.29
3D	0.015”	0.40 second	0.78	0.91	0.93
Measured	0.040”	0.70 second	**0.52**	**0.51**	**N/A**
Measured	0.015”	0.40 second	**0.43**	**0.38**	**N/A**

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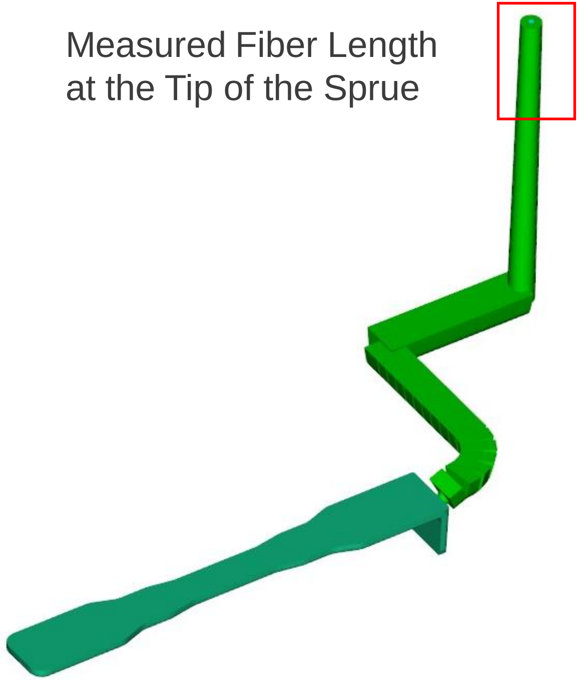
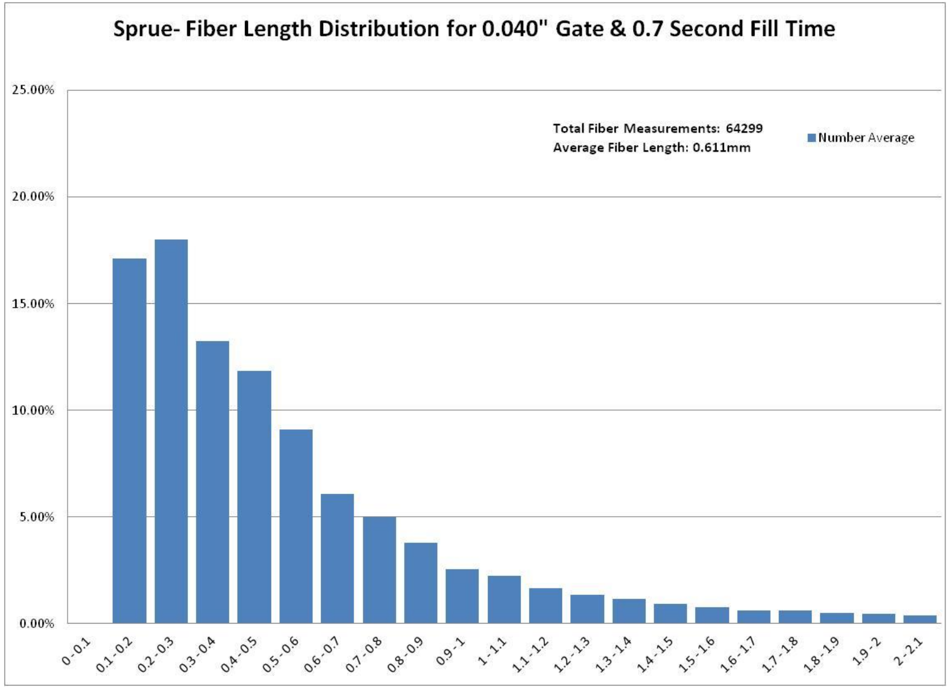
Fiber Breakage Study: Inlet Conditions Measurements

Measured Fiber Length at the Tip of the Sprue





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Fiber Breakage Study: Measurements With Inlet

Solver	Gate	Fill Time	Gate (Number Average)	Middle (Number Average)	End (Number Average)
Midplane	0.040”	0.70 second	6.73 **[1.44]**	6.98 **[1.47]**	7.63 **[1.51]**
Midplane	0.015”	0.40 second	6.68 **[1.43]**	6.91 **[1.46]**	7.42 **[1.50]**
3D	0.040”	0.70 second	0.78 **[0.48]**	1.24 **[0.54]**	1.29 **[0.55]**
3D	0.015”	0.40 second	0.78 **[0.45]**	0.91 **[0.53]**	0.93 **[0.53]**
Measured	0.040”	0.70 second	0.52	0.51	N/A
Measured	0.015”	0.40 second	0.43	0.38	N/A

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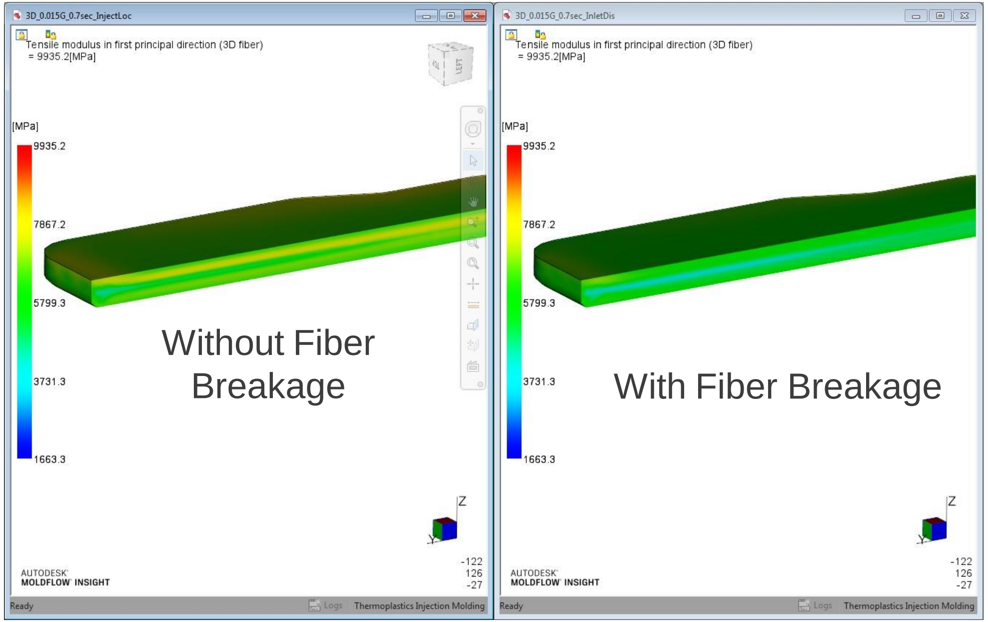
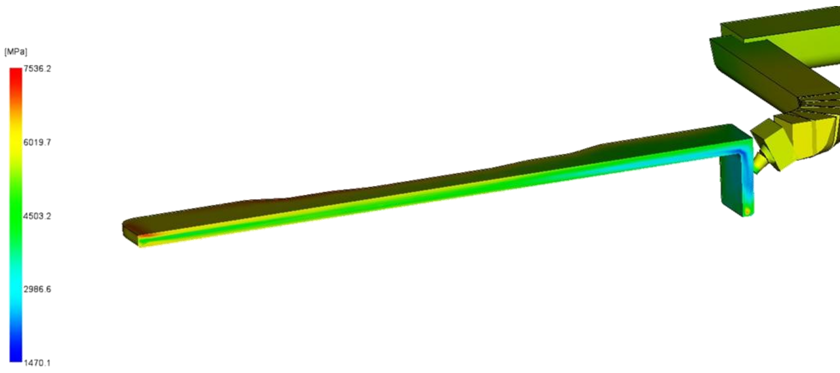
Correlation Study: Results

- Tensile Modulus in First Principal Direction





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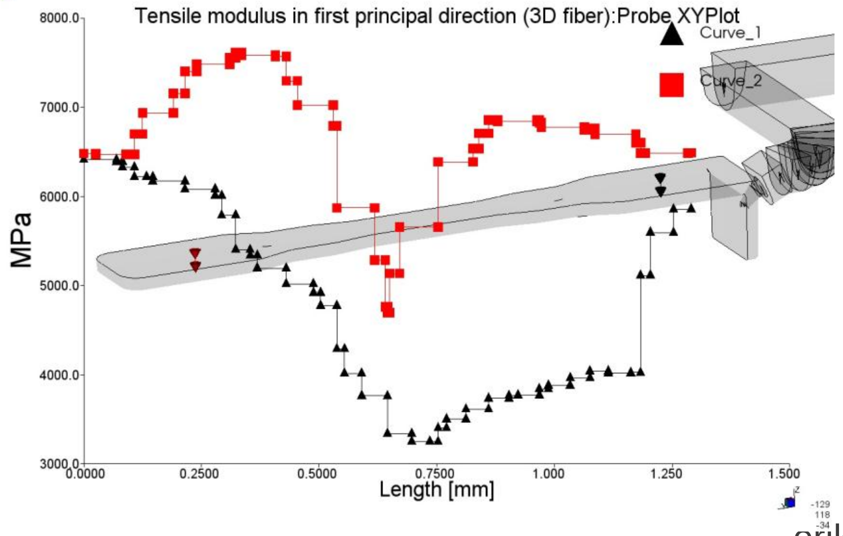
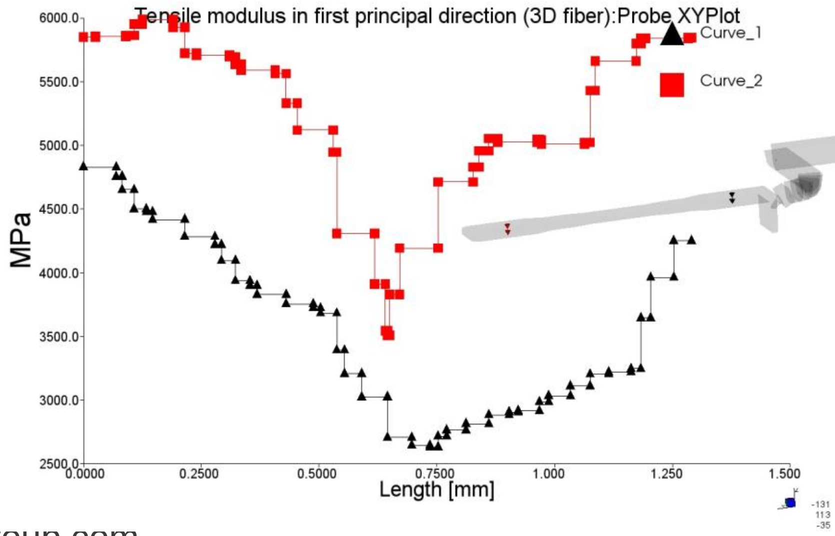
Predicted Mechanical Properties With and Without Fiber Breakage Implemented

- Tensile Modulus in First Principal Direction

0.040” Diameter Gate; 0.70 sec. Fill Time
Without Fiber Breakage



0.040” Diameter Gate; 0.70 sec. Fill Time
With Fiber Breakage



erik@madisongroup.com
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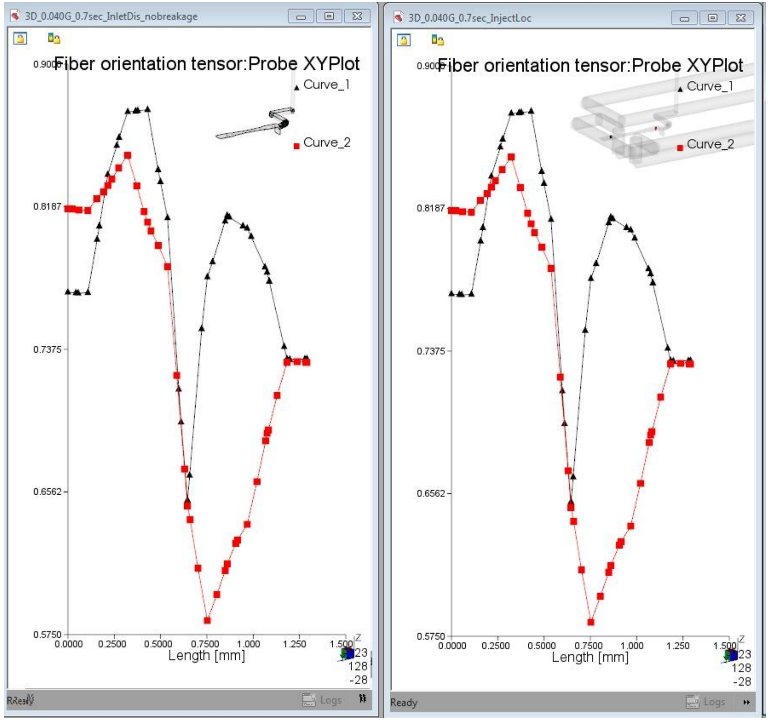
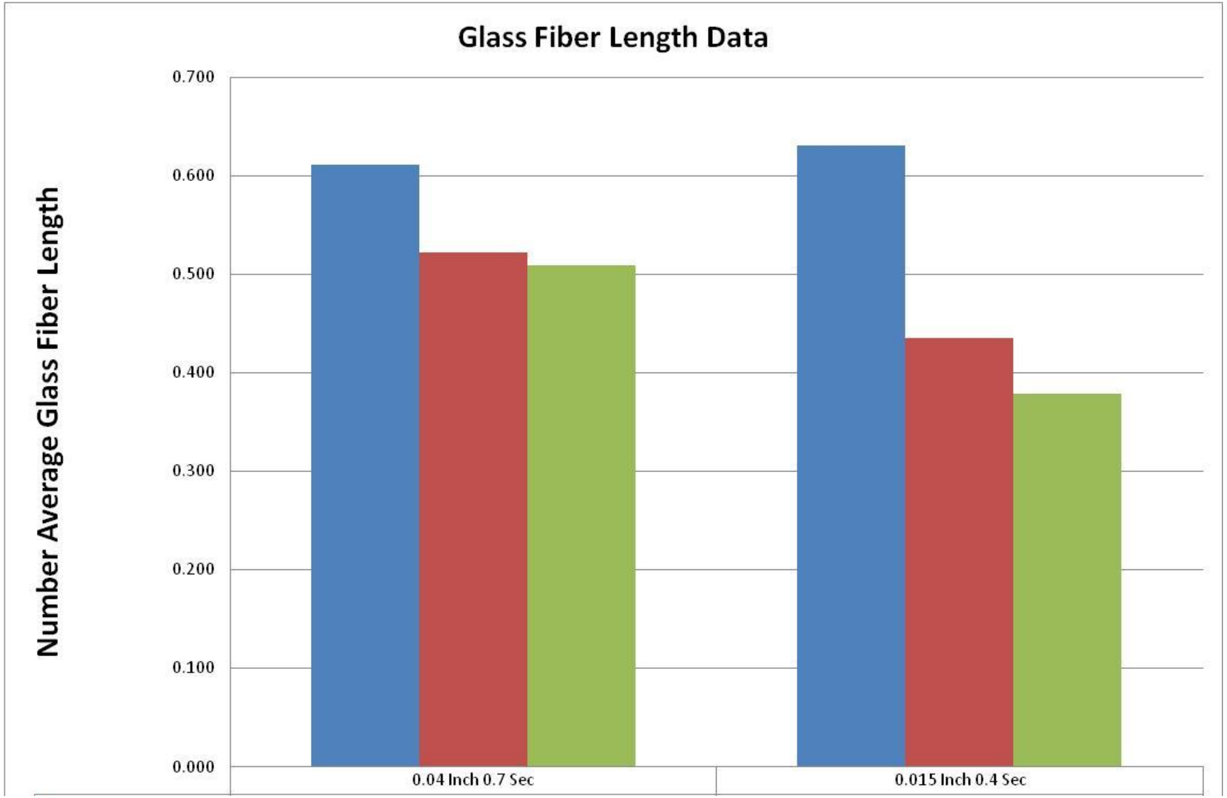
Predicted Fiber Orientation With and Without Fiber Breakage Implemented

- Fiber Orientation Prediction is the Same With and Without Fiber Breakage
- Therefore, Differences are a Result of Fiber Breakage



Correlation Study: Results



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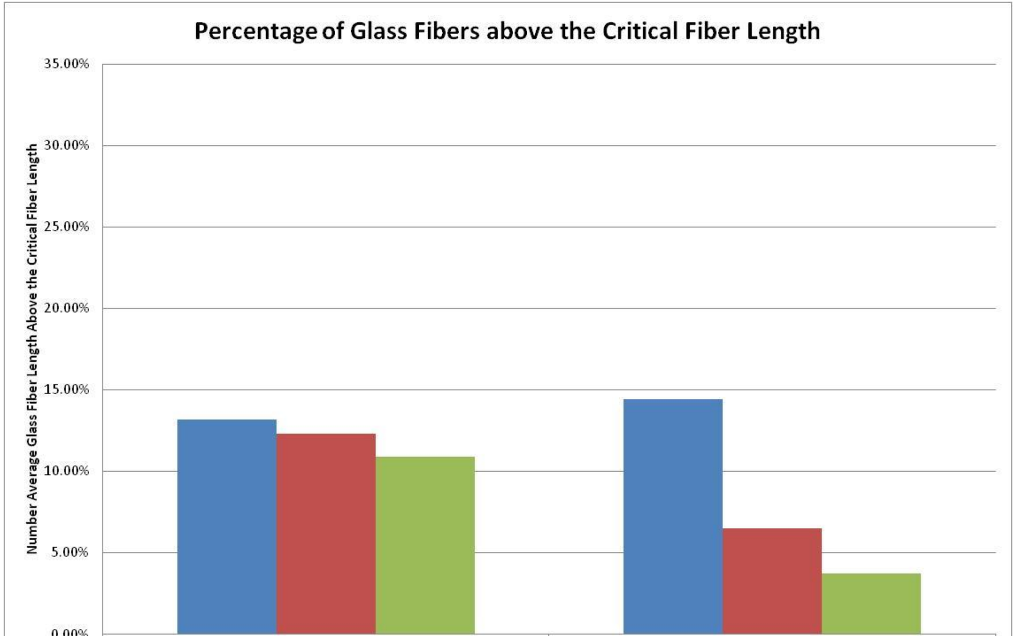
Correlation Study: Number of Fibers Above Critical Length

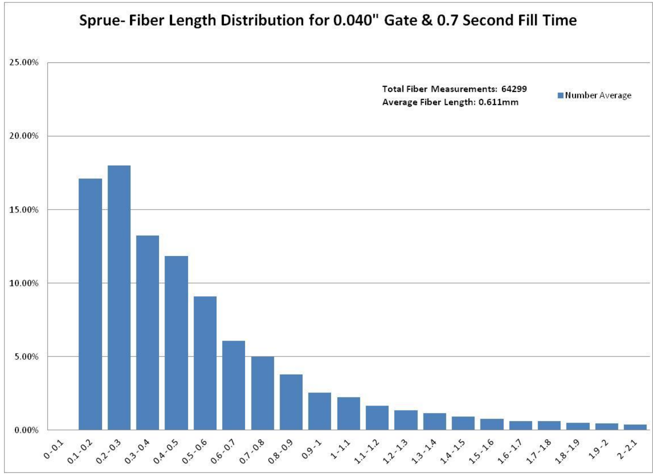


	0.04 Inch 0.7 Sec	0.015 Inch 0.4 Sec
Sprue	13.16%	14.43%
Gate	12.33%	6.52%
Middle	10.90%	3.72%

erik@madisongroup.com
Madisongroup.com

Conclusion

- When Selecting Discontinuous Glass-Reinforced Composites it is Important to Account for the Effects of Processing on the Performance of the Material
  - Fiber Orientation
  - Fiber Length
- Fiber Breakage Code Can Provide a Indications of Fiber Length Trends
- How the Melt is Prepared is More Critical than Gate Design and Sizing for Maintaining Fiber Length
- A Method of Measuring a Large Number of Fibers in Different Areas Has Been Developed to Characterize the Fiber Length Distribution



erik@madisongroup.com
Madisongroup.com

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erik@madisongroup.com
Madisongroup.com