RELIABILITY AND SURVIVABILITY ANALYSIS OF 3D PRINTED FDM PARTS

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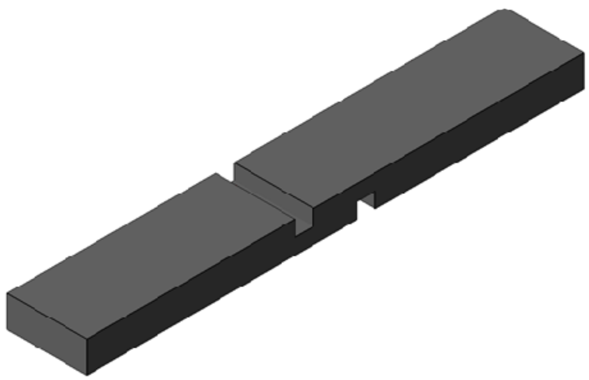
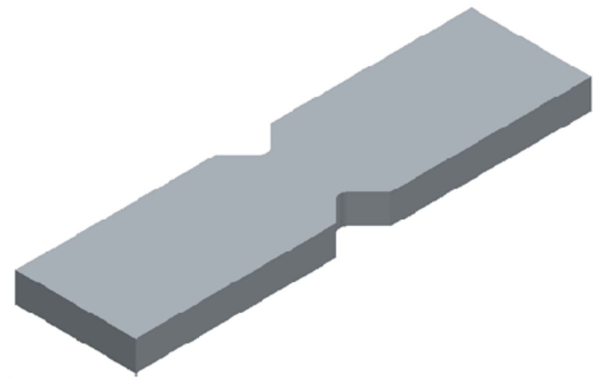
Objectives

- Introduce AM to the US Army AMRDEC's S&T program entitled "PRIntable Materials with embedded Electronics (PRIME2)
- Investigate state-of-the-art 3D fabrication capabilities for electronics
- Reduce weaponry size/weight/cost and increase efficiency
- Further investigate 3D Printing of entire PCB (antenna, RF structures, connectors)

Test Specimens and Methods





- In-Plane Shear Test Specimen
- ASTM D3846 Method

- V-Notch Test Specimen
- ASTM D5379/D Method

Note: ASTM D1892 standard has been used for Extrusion/Forming Sheet process.

Test Materials

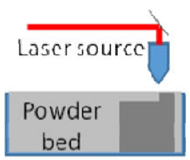
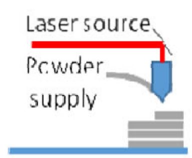
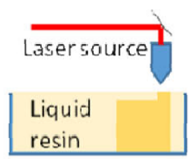
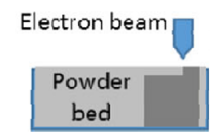
The materials that have been used in this study are:

- ❖ABS: Acrylonitrile Butadiene Styrene
- ❖HIPS: High Impact Poly-Styrene
- ❖PLA: Poly-Lactic Acid

Two different manufacturing processes:

1. 3D Printing process (FDM) using the recommendation of the 3D Printer manufacturer.
2. Conventional Extrusion/Forming Sheet process: The specimens are cut from sheets of plastics, which are prepared using ASTM D1892 standard

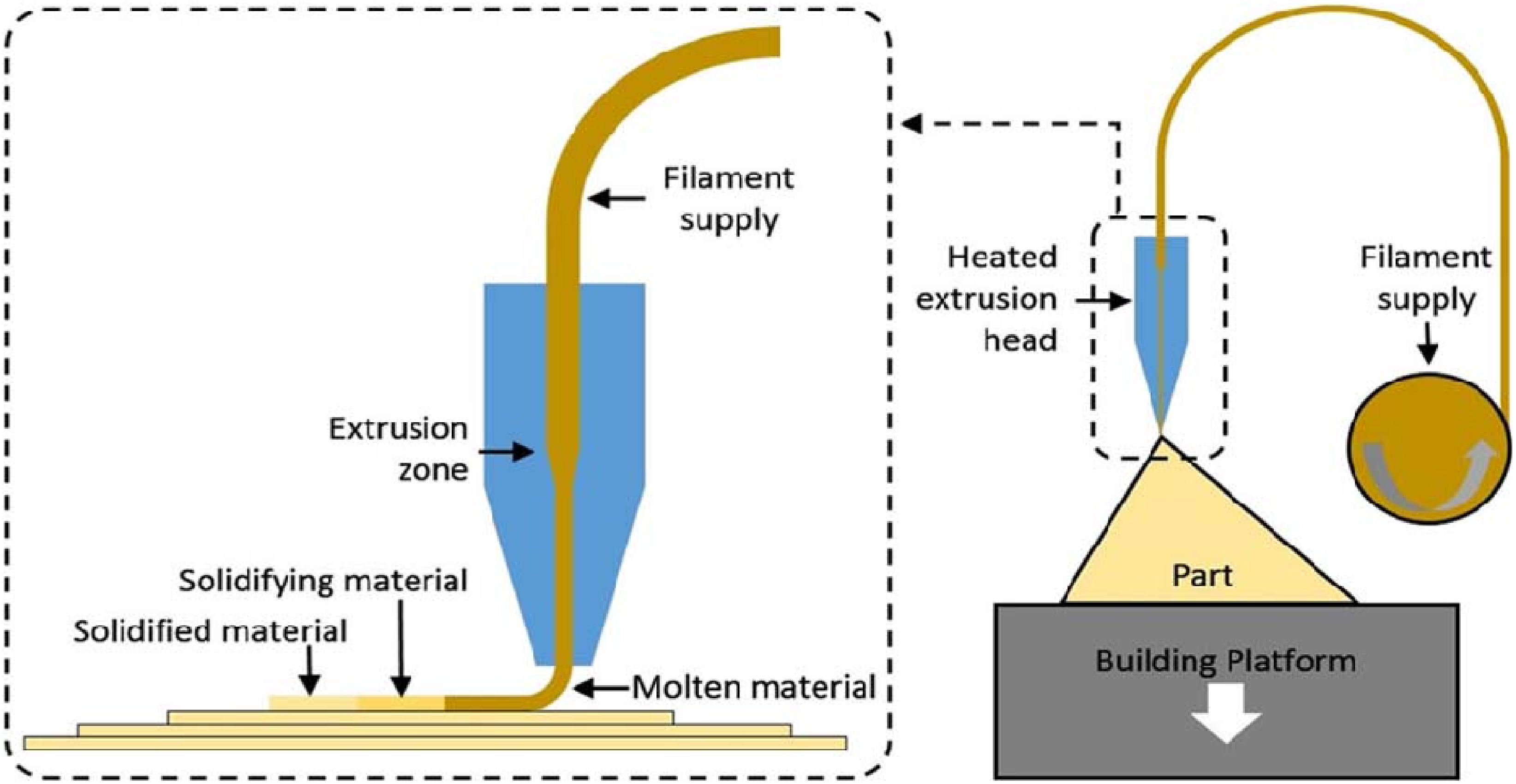
Additive Manufacturing Processes

Additive Manufacturing (AM) Processes							
Process	**Laser Based AM Processes**			**Extrusion Thermal**	**Material Jetting**	**Material Adhesion**	**Electron Beam**
	Laser Melting		***Laser Polymerization***				
Process Schematic							
Name / Material	SLS	DMD	SLA	FDM	3DP	LOM	EBM
	SLM	LENS	SGC	Robocasting	IJP	SFP	
	DMLS	SLC	LTP		MJM		
		LPD	BIS		BPM		
			HIS		Thermojet		
Bulk Material Type	Powder	Liquid	Solid				

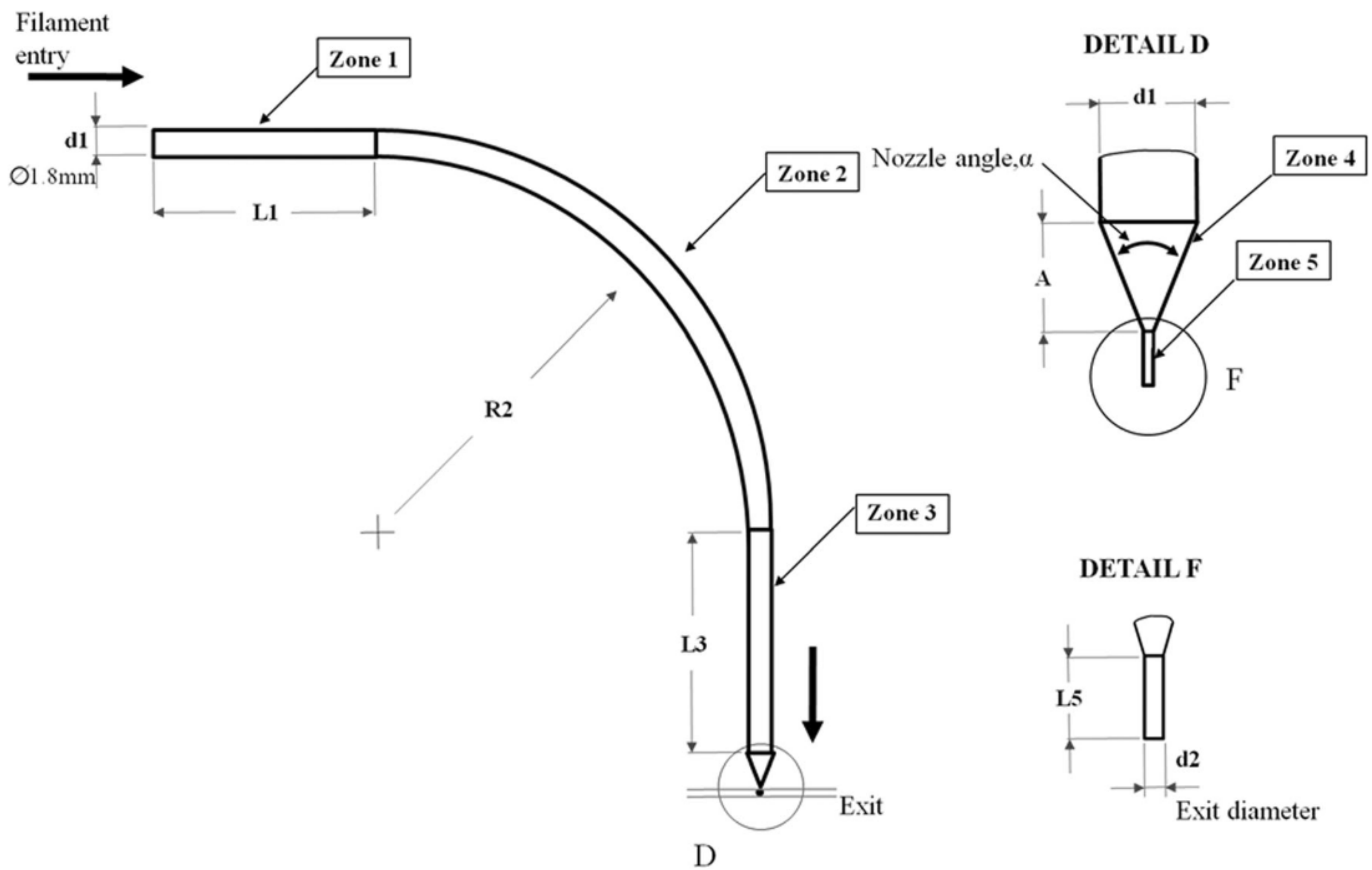
Additive Manufacturing Technique and Basic Elements

Table 4	Additive Manufacturing Technique and Basic Elements							
Am Process	Monitored Attribute							
	Laser Power/ Distribution	Melt Pool Temperature	Nozzle Temperature	Jet Status	Chamber Temperature	Chamber Vacuum	Platform Position	Head Position
Laser Polymerization Process	X				X	X	X	X
Laser Melting Process	X	X			X	X	X	X
Extrusion Process		X	X		X		X	X
Material Jetting Processes				X	X		X	X
Adhesive Processes					X		X	X

Modelling Approach - Extrusion processes (FDM)



The Extrusion Process



Sectional view of melt flow channels showing five zones

The Extrusion Processes

- **The pressure drop (ΔP) in a capillary rheometer required that a non-Newtonian fluid be driven through a tube of length *l* and radius r is:**

where:

η_α	**Apparent viscosity determined using a capillary rheometer**
Q	**Volumetric flow rate**

- $\Delta P = \Delta P_1 + \Delta P_2 + \Delta P_3 + \Delta P_4 + \Delta P_5$

Pressure Drop in Every Zone

$\Delta P = \Delta P_1 + \Delta P_2 + \Delta P_3 + \Delta P_4 + \Delta P_5$

where:

$$\Delta P_1 = 2L_1\left(\frac{V}{\emptyset}\right)^{\frac{1}{m}}\left(\frac{m+3}{r_1^{m+1}}\right)^{\frac{1}{m}}\exp\left[\alpha\left(\frac{1}{T-T_0} - \frac{1}{T_\alpha - T_0}\right)\right]$$

$$\Delta P_2 = 2L_2\left(\frac{V}{\emptyset}\right)^{\frac{1}{m}}\left(\frac{m+3}{r_1^{m+1}}\right)^{\frac{1}{m}}\exp\left[\alpha\left(\frac{1}{T-T_0} - \frac{1}{T_\alpha - T_0}\right)\right]$$

$$\Delta P_3 = 2L_3\left(\frac{V}{\emptyset}\right)^{\frac{1}{m}}\left(\frac{m+3}{r_1^{m+1}}\right)^{\frac{1}{m}}\exp\left[\alpha\left(\frac{1}{T-T_0} - \frac{1}{T_\alpha - T_0}\right)\right]$$

$$\Delta P_4 = \frac{2m}{3\tan\left(\frac{\alpha}{2}\right)}\left(\frac{1}{r_2^{\frac{1}{m}}} - \frac{1}{r_1^{\frac{1}{m}}}\right)\left(\frac{V}{\emptyset}\right)^{\frac{1}{m}}\left[r_1^2 2^{m+3}(m+3)\right]^{\frac{1}{m}}\exp\left[\alpha\left(\frac{1}{T-T_0} - \frac{1}{T_\alpha - T_0}\right)\right]$$

1 1

Pressure Drop in Every Zone

where:

$L_1 - L_3$ and L_5 length of respective zones

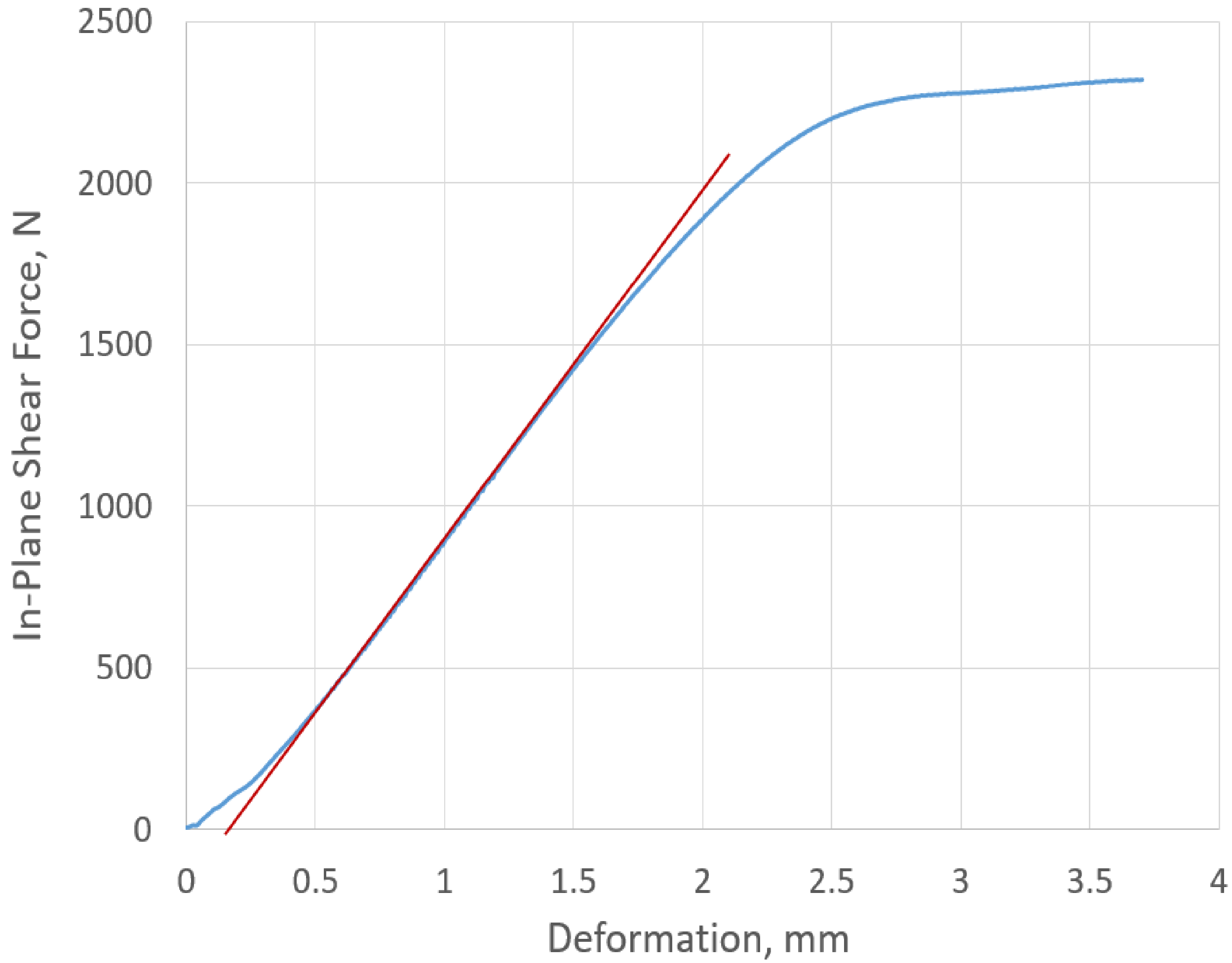
$L_2 = \left(\pi(R_2 + d_1/2)\right)/2$

R_2	radius of the channel at zone 2
r_1	radius of the cylindrical area of the melt flow channel
r_2	the exit radius
α	nozzle angle
V	filament velocity at the entry
u	fluidity
m	flow exponent
T	working temperature
T_a	the temperature at which m and u are calculated

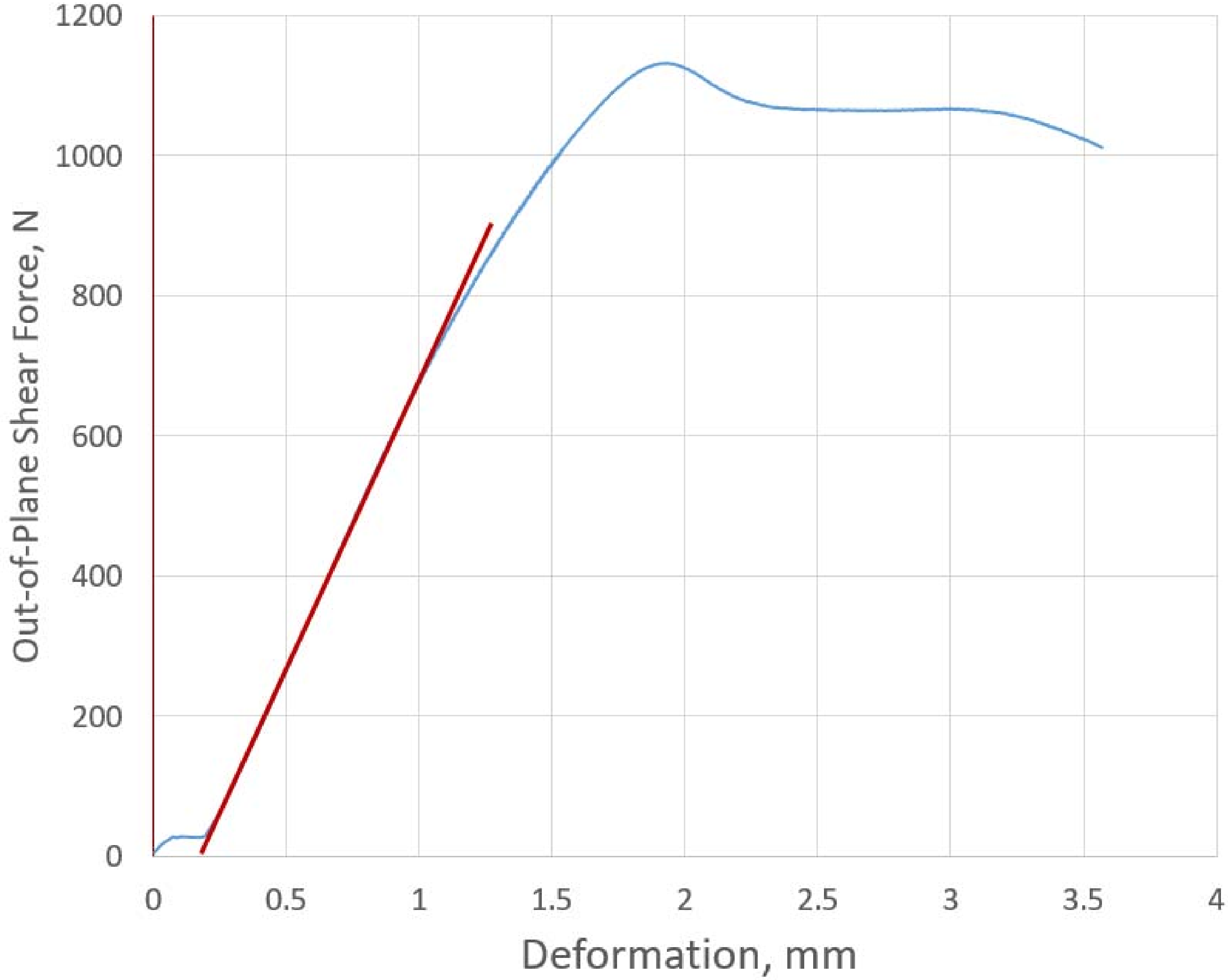
3D Printing Conditions of the Filaments

Variables	ABS
Extrusion Temperature	240 °C
Layer Thickness	0.05mm – 0.50mm
Bed Temperature	110 °C
Chamber Temperature	N/A
Filament Size	3mm
Nozzle Diameter	0.50mm
Infill	100%

Typical In-Plane Shear Test



Typical V-Notch Shear Test



In-Plane Shear Test Results (3-D Printer)

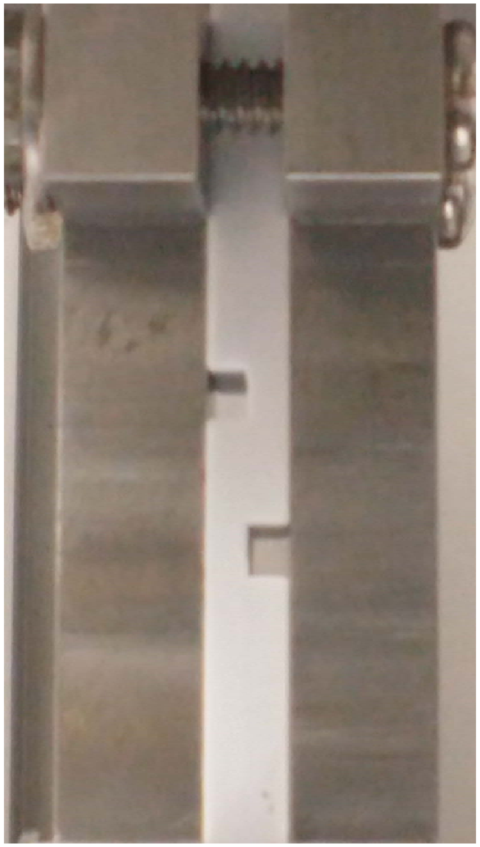
Statistical Values	ABS – 3D Printer		HIPS – 3D Printer		PLA – 3D Printer	
	Prop. Limit	In-Plane Shear	Prop. Limit	In-Plane Shear	Prop. Limit	In-Plane Shear
Average	20.2 MPa	32.1 MPa	19.9 MPa	30.4 MPa	29.95 MPa	44.4 MPa
Standard Deviation	0.455 MPa	1.366 MPa	0.297 MPa	0.649 MPa	1.155 MPa	1.354 MPa
Coefficient of Variance	2.25%	4.25 %	1.50 %	2.13 %	3.86 %	3.05 %

V-Notch Shear Test Results (3-D Printer)

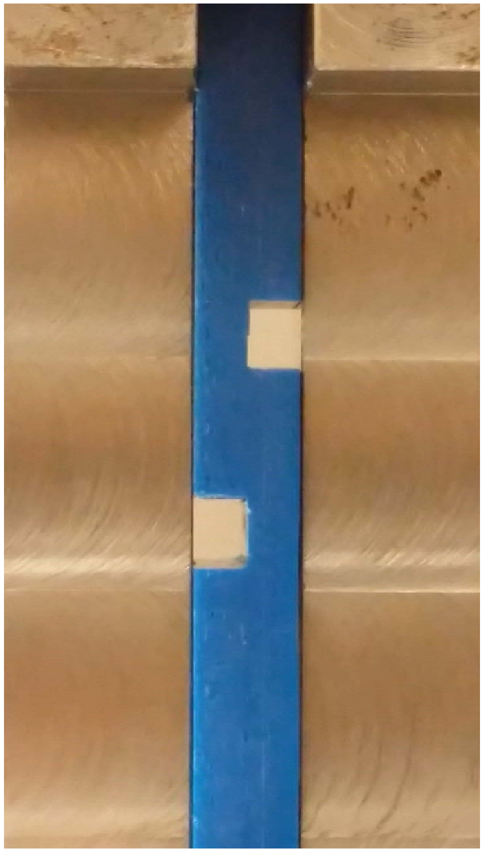
Statistical Values	ABS – 3D Printer		HIPS – 3D Printer		PLA – 3D Printer	
	Prop. Limit	In-Plane Shear	Prop. Limit	In-Plane Shear	Prop. Limit	In-Plane Shear
Average	**21.5 MPa**	**30.8 MPa**	**20.3 MPa**	**25.1 MPa**	**34.98 MPa**	**46.9 MPa**
Standard Deviation	**0.26 MPa**	**0.27 MPa**	**0.65 MPa**	**0.56 MPa**	**1.65 MPa**	**0.59 MPa**
Coefficient of Variance	**1.2%**	**0.878 %**	**3.22 %**	**2.25 %**	**4.71 %**	**1.24 %**

Typical In-Plane Shear Test

Extrusion/Forming Sheet



3D Printing

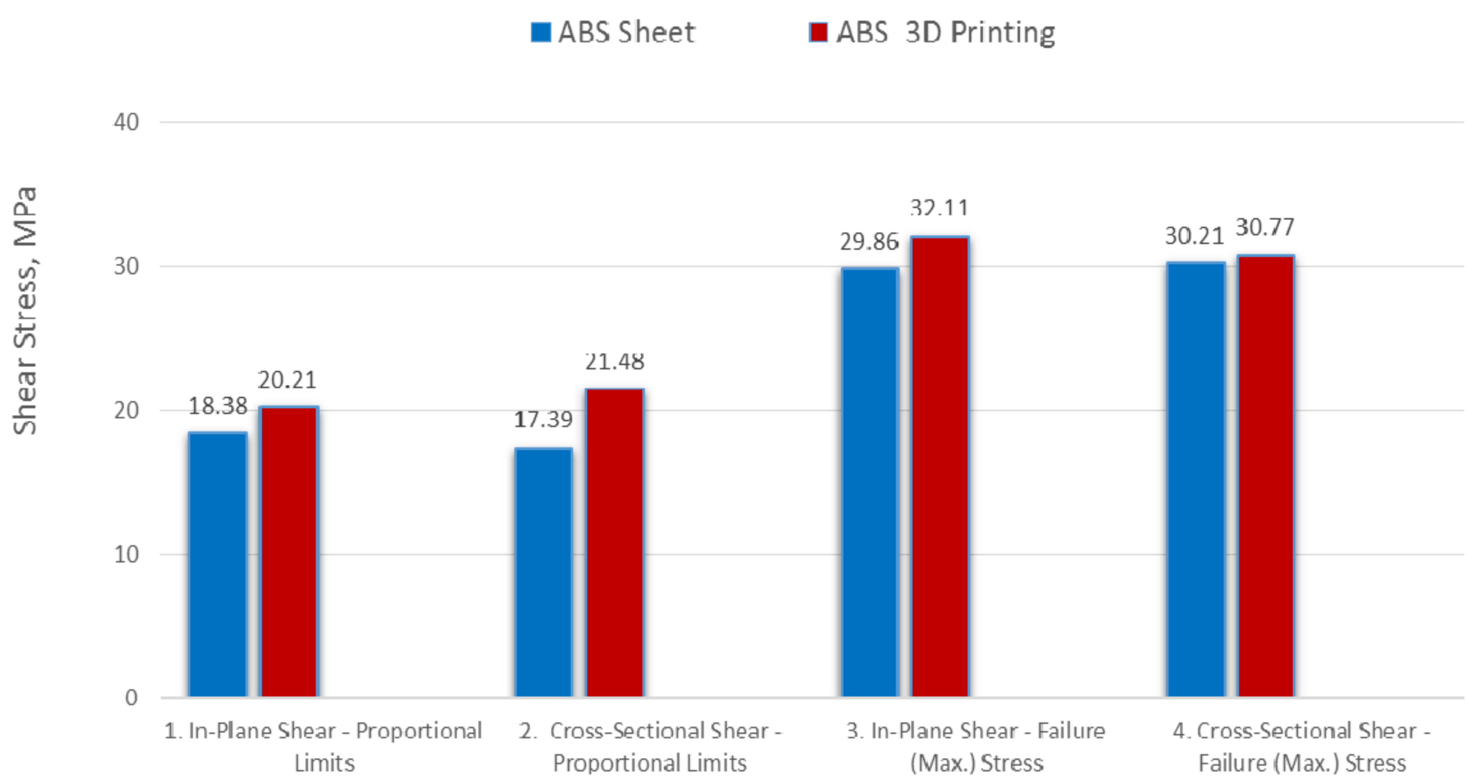


Typical V-Notch Shear Test

Extrusion/Forming Sheet

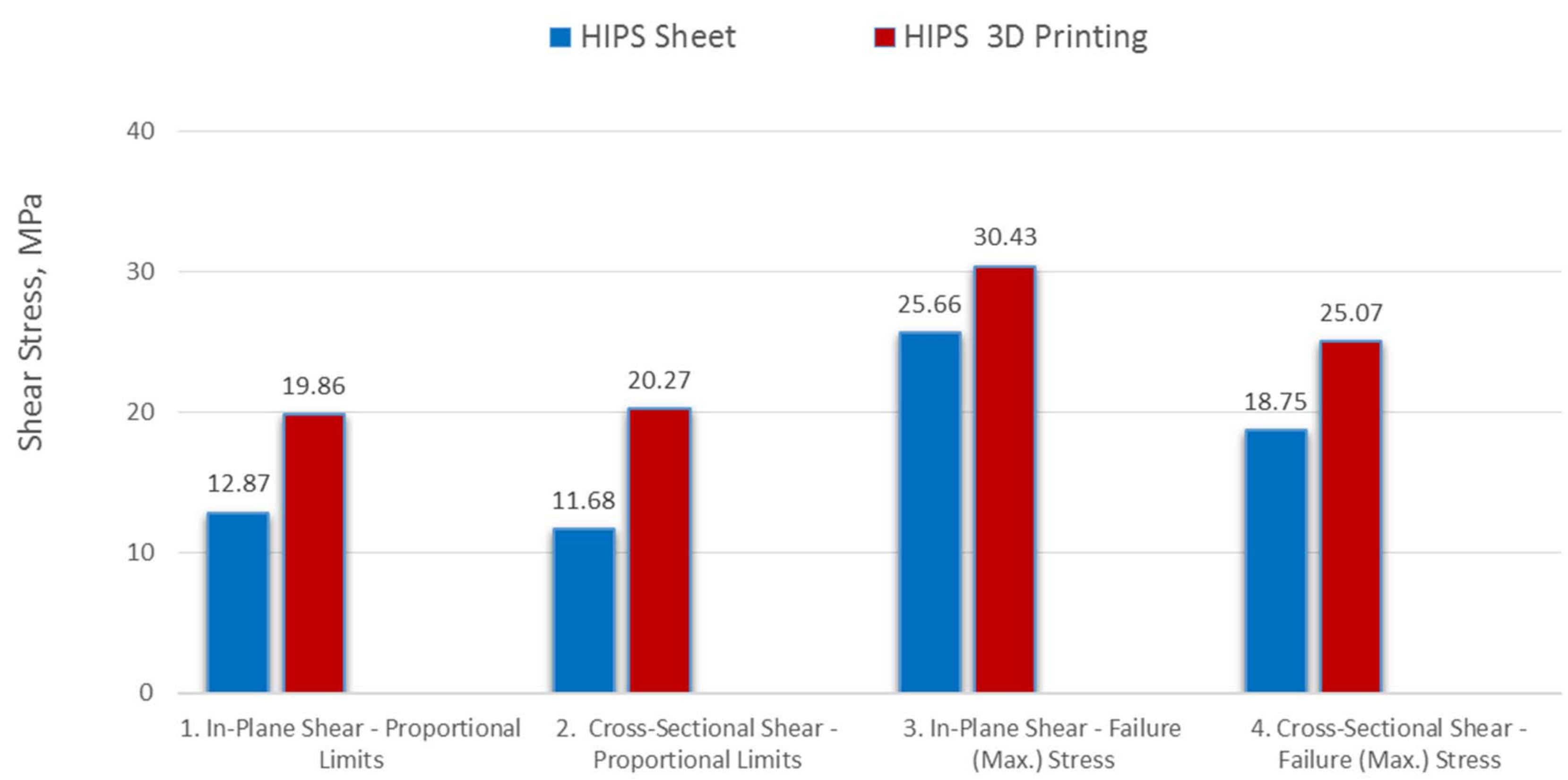
3D Printing

ABS sheets VS ABS 3D Printed (Acrylonitrile Butadiene Styrene – ABS)



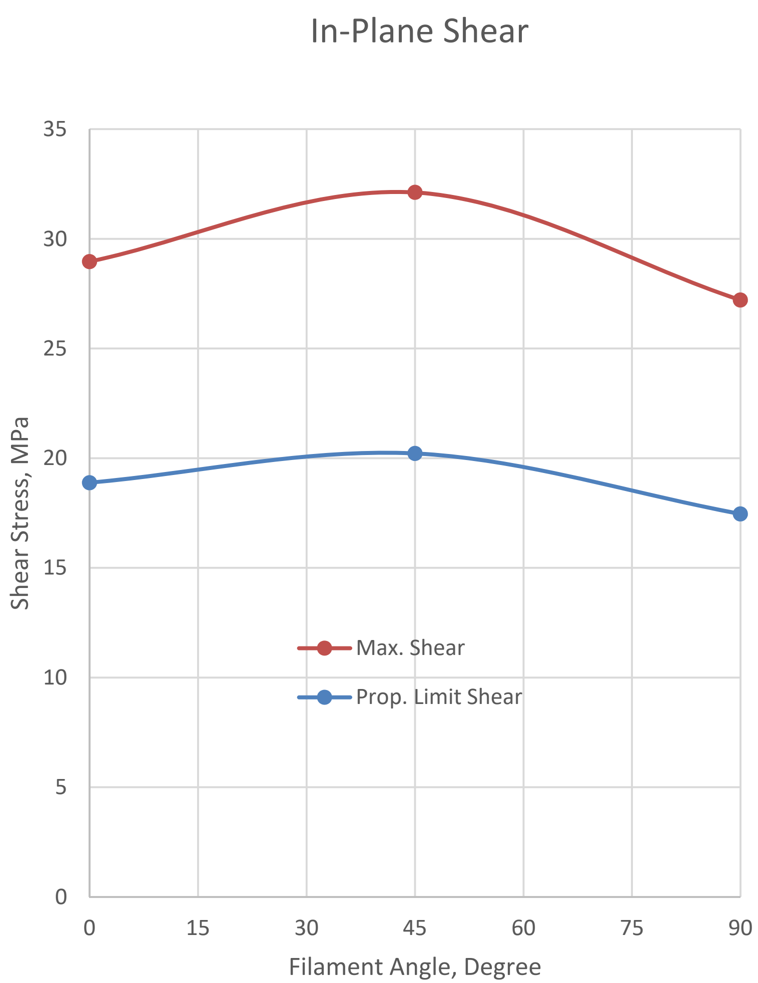
NOTE: 3D printed coupons are JUST AS STRONG or STRONGER !!!

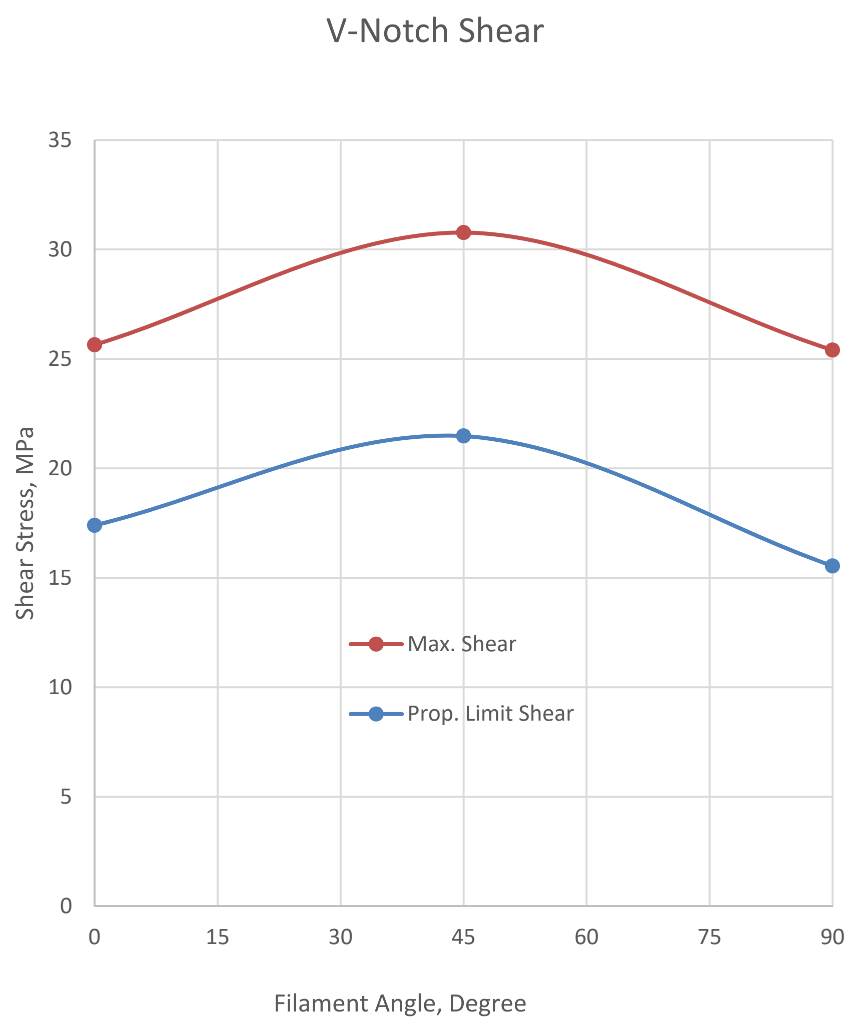
HIPS sheets VS HIPS 3D Printed (High Impact Poly-Styrene, i.e., HIPS)



NOTE: 3D printed coupons are JUST AS STRONG or STRONGER !!!

Effect of Filament Orientation



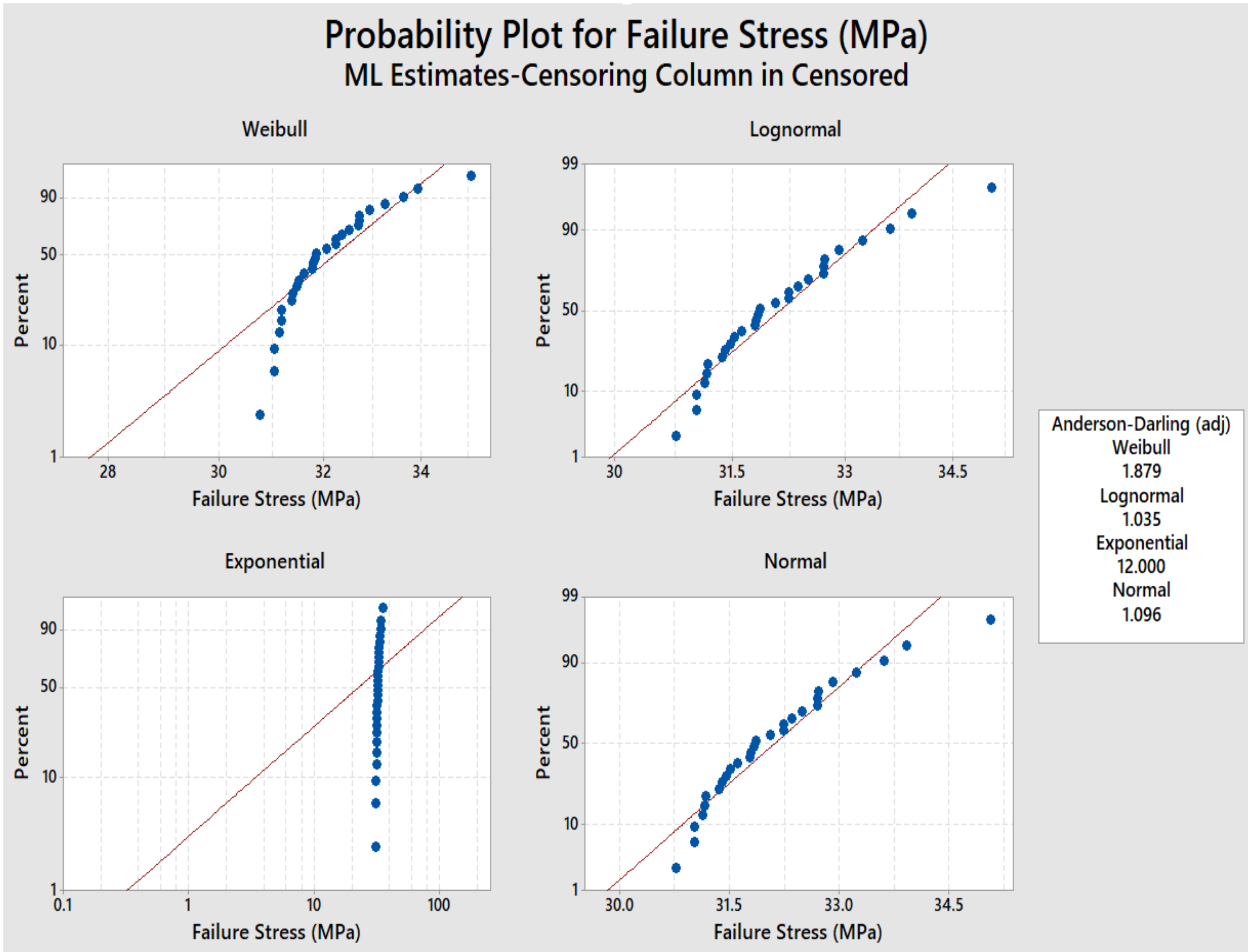


Failure and Quality Assessment Analysis

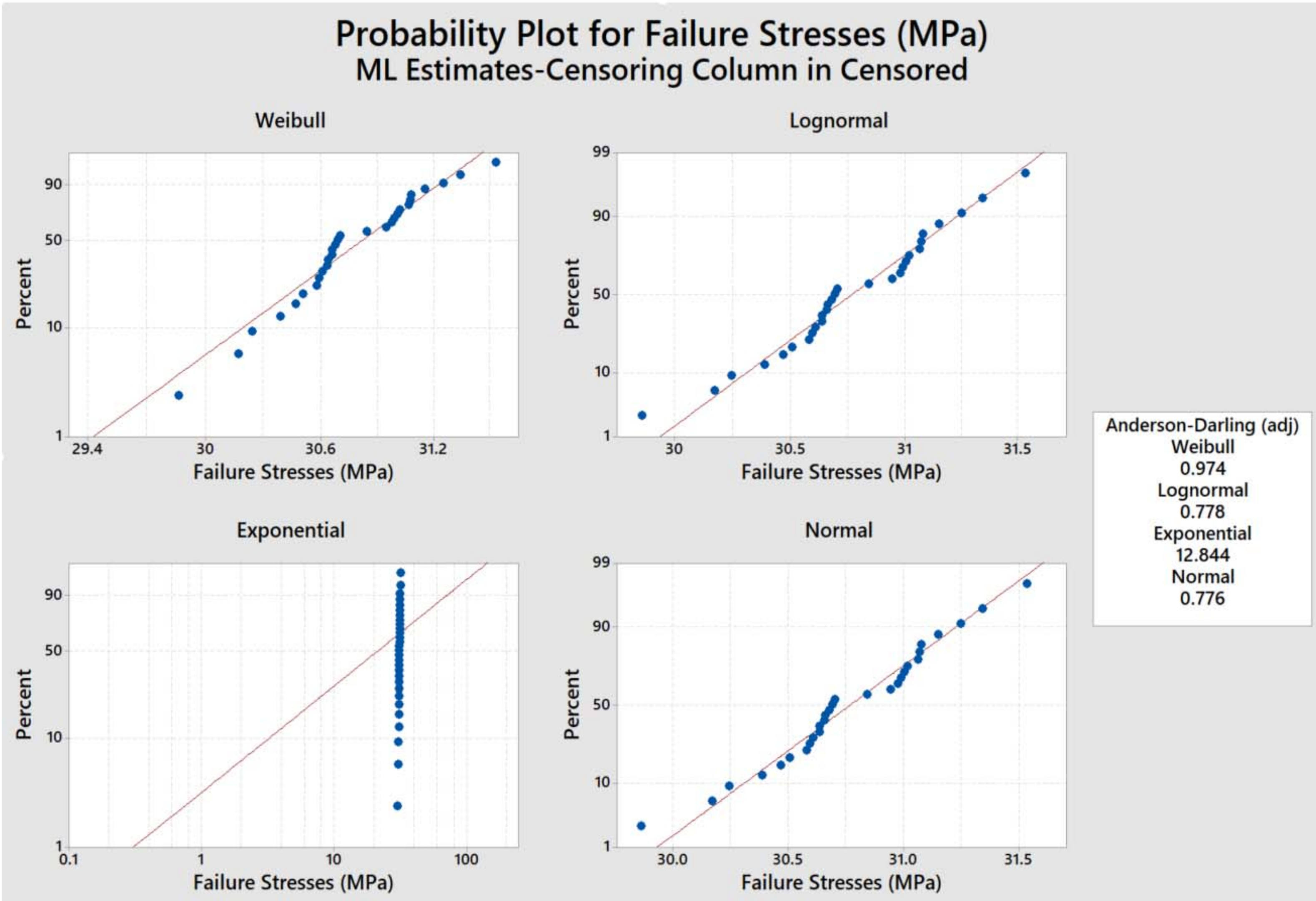
In this work, four distributions have been examined:

1. **Weibull Distribution**
2. **Lognormal Distribution**
3. **Exponential Distribution**
4. **Normal Distribution**

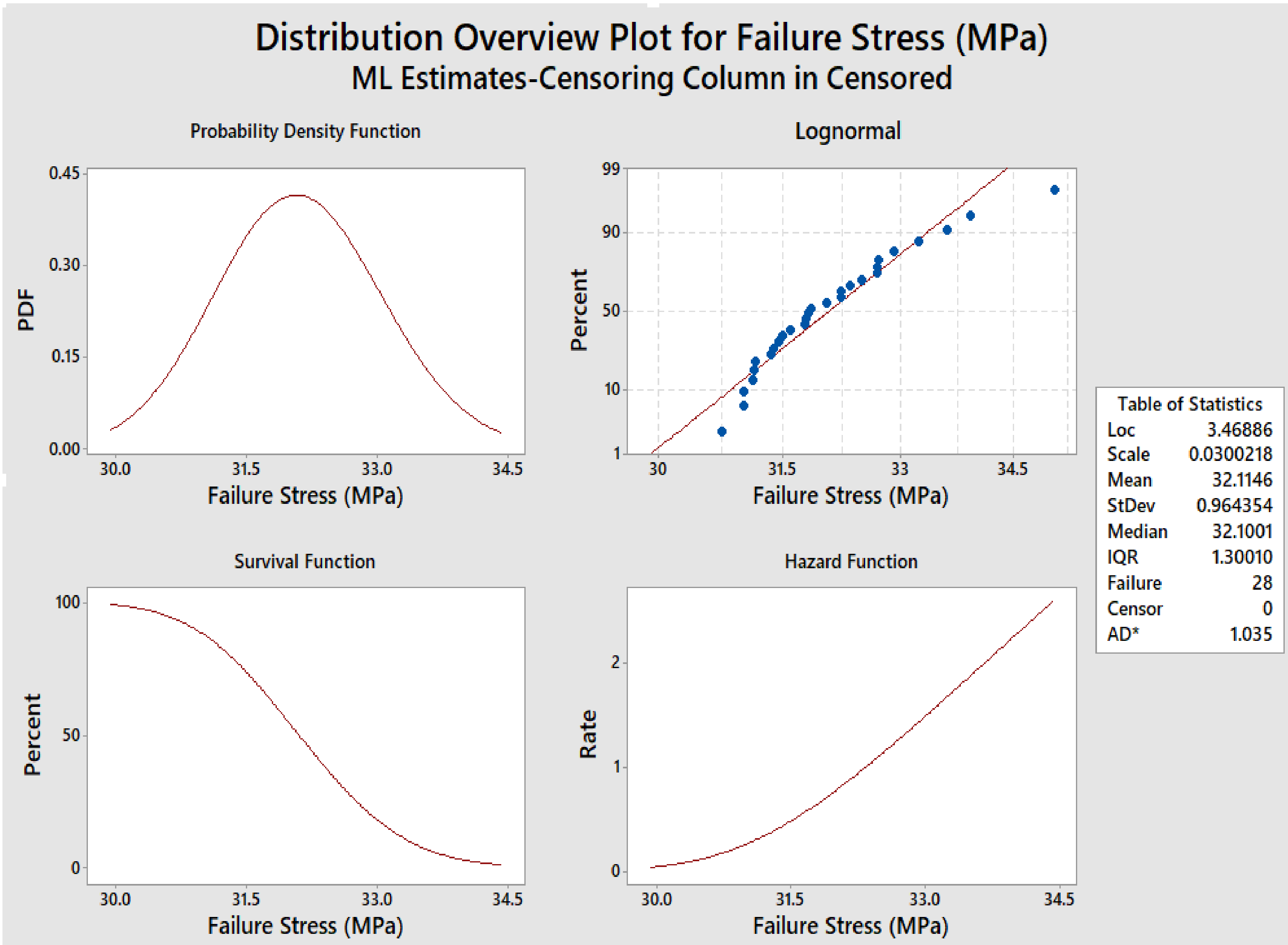
Probability Plot for Failure Stresses for In-Plane Shear Data



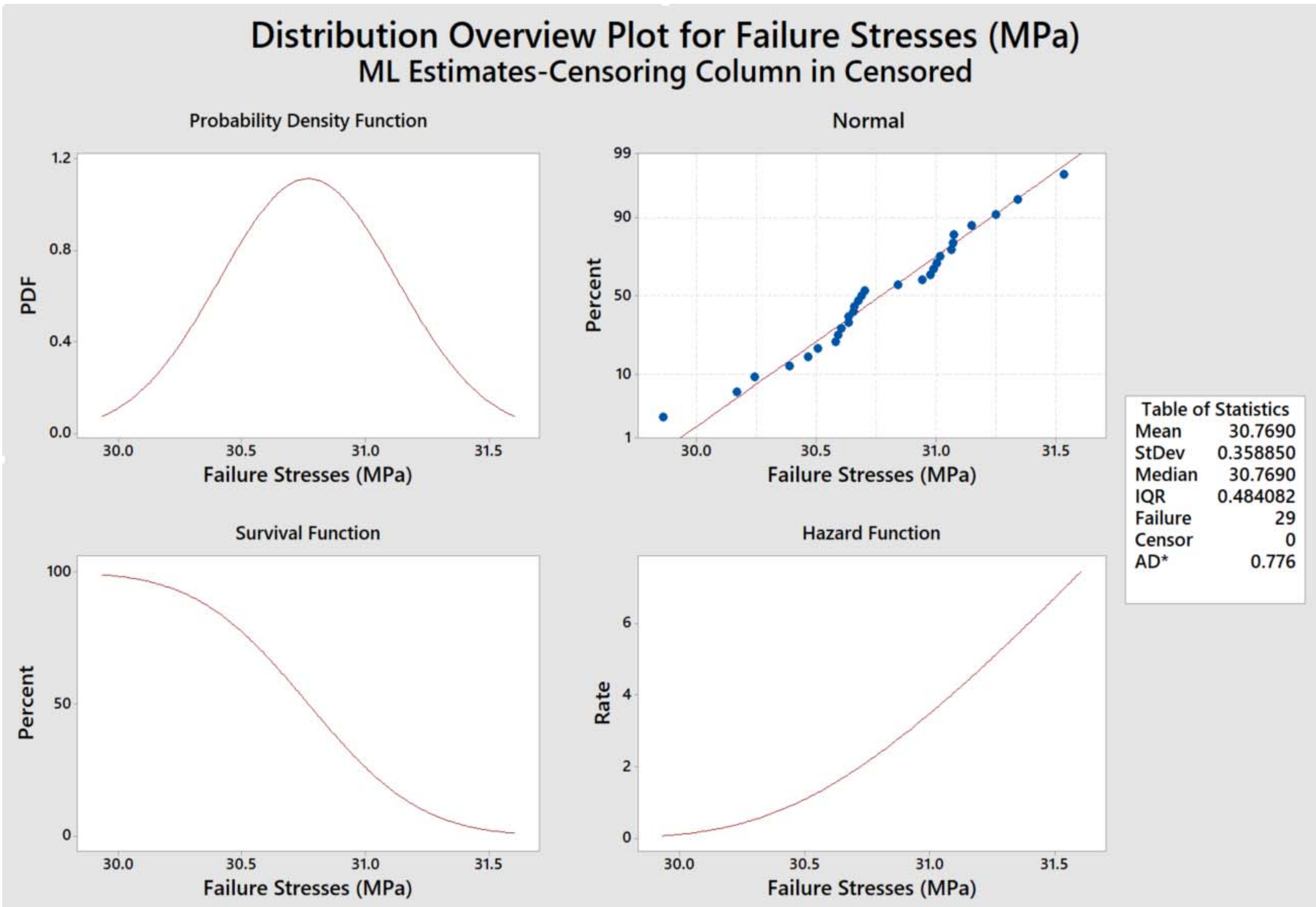
Probability Plot for Failure Stresses for V-Notch Shear Data



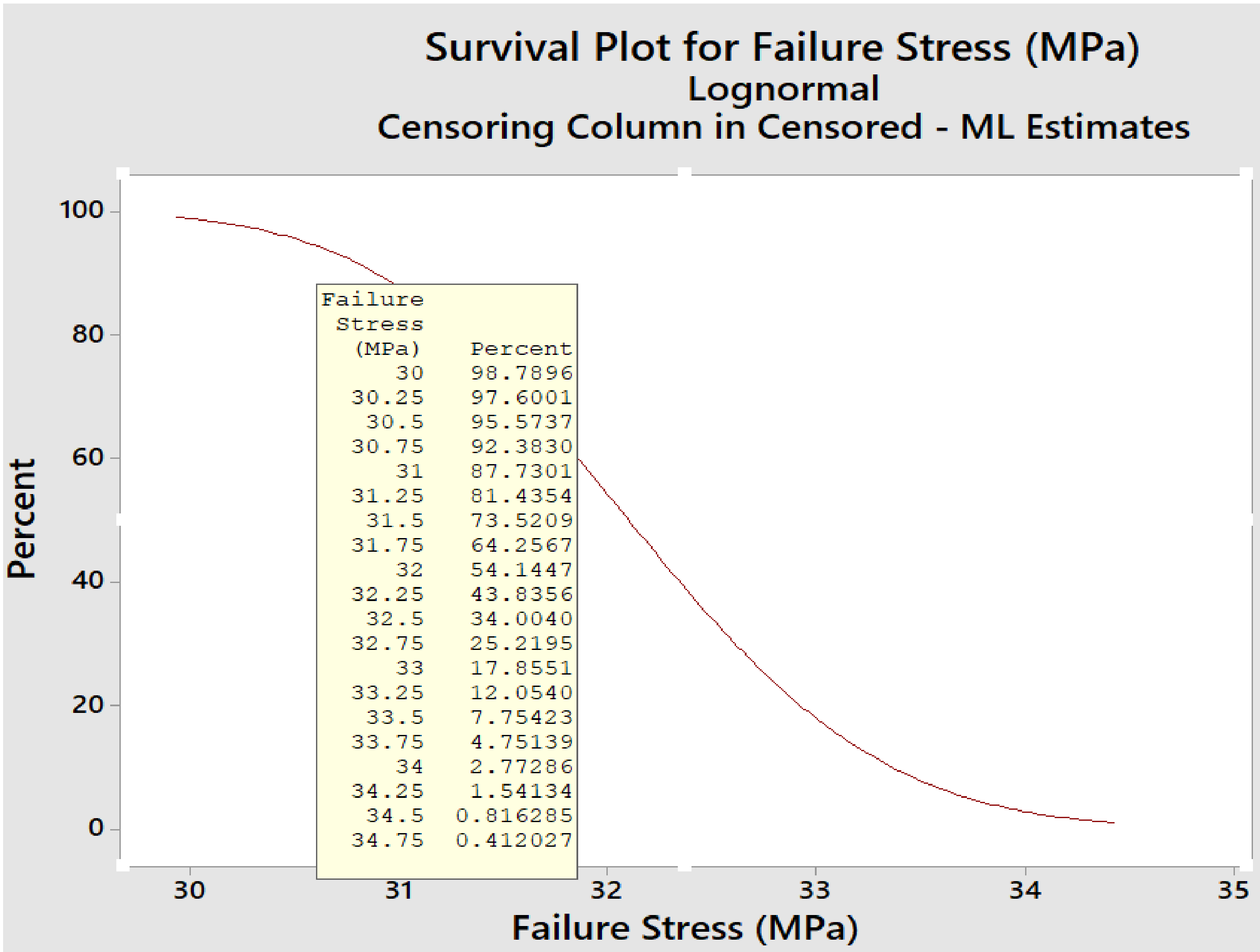
Distribution Plot for Failure Stresses for In-Plane Shear Data



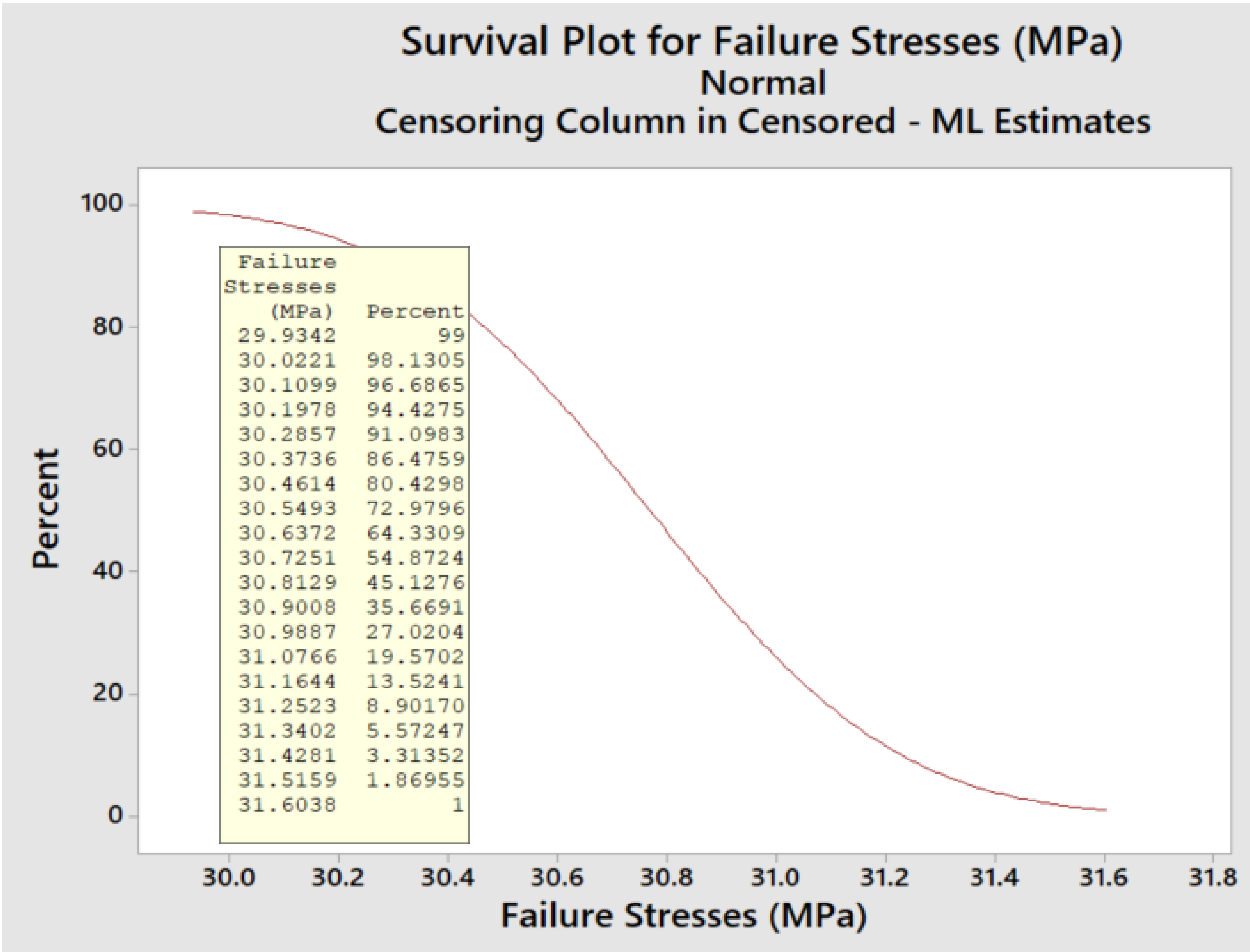
Distribution Plot of Failure Stresses for V-Notch (out-of-plane) Shear Data



Survival Probabilities at Different In-Plane Shear Stress Levels



Survival Probabilities at Different Out-of-Plane Shear Stress Levels



Comparison between 3D Printing and Commercial Manufacturing Process

a. The Mann-Whitney Test

Mann-Whitney: 3D, Commercial

Method

η_1: median of 3D
η_2: median of Commercial
Difference: $\eta_1 - \eta_2$

Descriptive Statistics

Sample	N	Median
3D	26	31.8171
Commercial	26	30.4876

Estimation for Difference

Difference	CI for Difference	Achieved Confidence
1.23197	(0.502332, 1.90291)	95.09%

Test

Null hypothesis	$H_0: \eta_1 - \eta_2 = 0$
Alternative hypothesis	$H_1: \eta_1 - \eta_2 \neq 0$

Method	W-Value	P-Value
Not adjusted for ties	852.00	0.003
Adjusted for ties	852.00	0.003

In-Plane

Mann-Whitney: 3D, Commercial

Method

η_1: median of 3D
η_2: median of Commercial
Difference: $\eta_1 - \eta_2$

Descriptive Statistics

Sample	N	Median
3D	26	30.6959
Commercial	26	28.7706

Estimation for Difference

Difference	CI for Difference	Achieved Confidence
1.98367	(1.85241, 2.20290)	95.09%

Test

Null hypothesis	$H_0: \eta_1 - \eta_2 = 0$
Alternative hypothesis	$H_1: \eta_1 - \eta_2 \neq 0$

W-Value	P-Value
1027.00	0.000

Out-of-Plane

b. Two sample Kolmogorov-Smirnov normality test

Kolmogorov-Smirnov 2-Sample Test

K-S Test Statistic: 0.576
K-S Critical Value (Approx): 0.377
Alpha Level: 0.05

The test statistic is greater than or equal to the critical value.

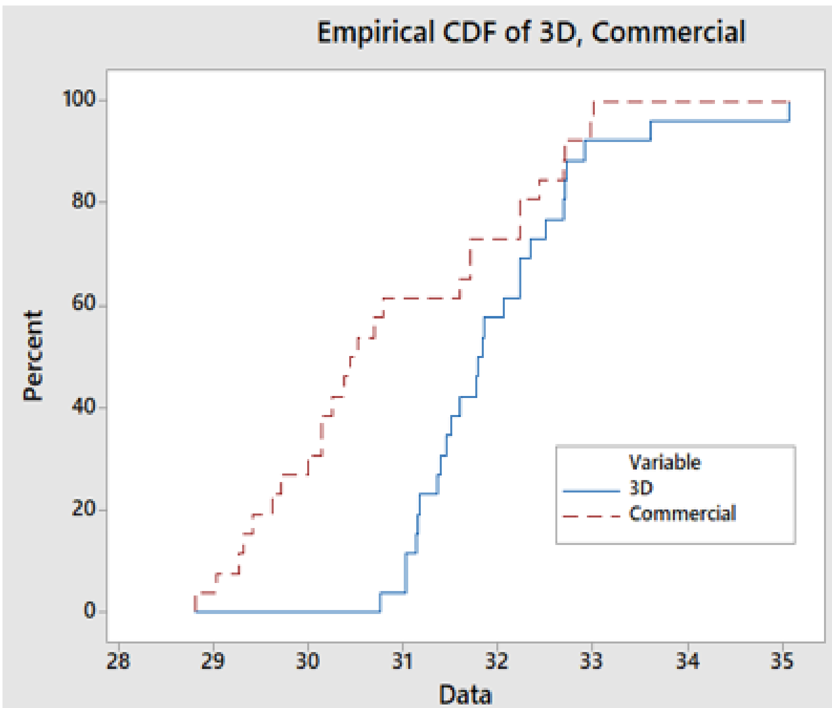
There is sufficient evidence to conclude that the underlying distributions are different.

Kolmogorov-Smirnov 2-Sample Test

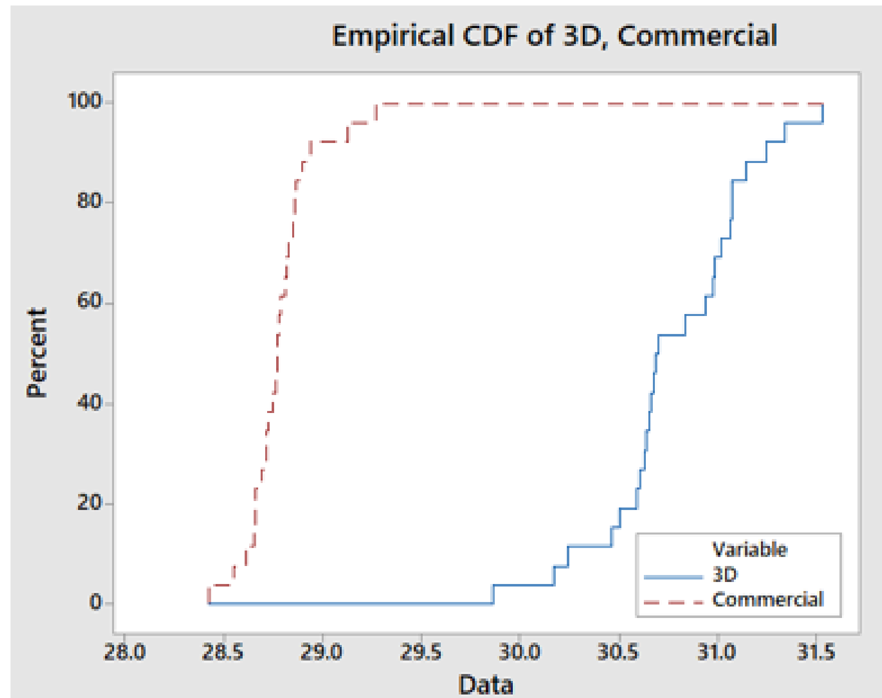
K-S Test Statistic: 1
K-S Critical Value (Approx): 0.377
Alpha Level: 0.05

The test statistic is greater than or equal to the critical value.

There is sufficient evidence to conclude that the underlying distributions are different.



In-Plane



Out-of-Plane

Conclusions

- ❖ **The COV never exceeds 5%.**
- ❖ **For In-Plane Shear, the ABS 3D specimens have about 7.54% higher stresses while the HIPS 3D specimens have about 18.6% increase in their shear stresses.**
- ❖ **For Cross-Sectional Shear, the ABS 3D specimens have about 23.5% higher proportional stresses. For HIPS filaments, HIPS 3D specimens have about 73.5 % increase in proportional limits.**
- ❖ **This increase would be attributed to the thermal cycling of the 3D printer process that would increase the material hardness and hence the Shear Stress.**
- ❖ **This study shows that more enhancement could be achieved by optimizing the effect of the different variables that affect the 3D printing process.**

Acknowledgements

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Thank You

Q & A