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Flexural Mechanical Properties and Microstructures of Three-Dimensional (3D) Printed Thermoplastics

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1. Introduction

Three-dimensional (3D) printing or additive manufacturing is utilized to manufacture products in industries of aerospace, automotive, and medical [1]. One example is General Electric (GE)'s decision to deploy 3D printers to manufacture nozzles for its LEAP engines. GE Aviation projects have printed more than 30,000 fuel nozzle tips in 2018 [2]. Manufacturing by 3D printing is experiencing an explosive growth and it is expected to grow to a market value of over $100 billion by 2030 [3]. Engineering components produced by 3D printing are employed as mechanical structures in an assembly. In order for the printed components to be useful for engineering applications, mechanical properties of printed parts must be known for structural design. These properties provide answers to the strength of material, the types of stresses a component can endure before failure, and the size of a component based on the loads it experiences. 3D printed materials have recently been studied for their mechanical properties [4], [5], [6], [7].

This study was undertaken to investigate flexural mechanical properties and microstructure effects of three-dimensional (3D) printed thermoplastics including acrylonitrile styrene acrylate (ASA), Polylactic Acid (PLA), and PolyJet material. This project also provided training in mechanical engineering research to a Mechanical Engineering Technology student. Test specimens are manufactured using the three-dimensional printing technologies of Fused Deposition Modeling and Liquid Jet employed by four 3D printers including Stratasys Fortus 450mc Printer (Figure 1), Stratasys J750 Digital Anatomy Printer (Figure 2), Stratasys Objet30 Printer (Figure 3), and MakerBot Replicator Z18 Printer (Figure 4). 3D printers, 3D printing technology, and raw material type are listed in Table 1.

Table 1. 3D Printer Features

Printer Name	3D Printing Technology	Raw Material Type
Stratasys Objet30	Liquid Jet	Liquid PolyJet
Stratasys J750	Liquid Jet	Liquid PolyJet
Stratasys Fortus 450mc	Fused Deposition Modeling (FDM)	acrylonitrile styrene acrylate (ASA)
MakerBot Replicator Z18	Fused Deposition Modeling (FDM)	Polylactic Acid (PLA)

2. Educational Aspect

The research project provided training in mechanical engineering research to a Mechanical Engineering Technology student at Queensborough Community College of The City University of New York. The training included conducting hands-on experiments, collecting experimental data using a computerized data acquisition system, calculating mechanical properties using Excel spreadsheet, analyzing experimental data, and writing a technical paper with a faculty member as mentor.

3. Experiment

3D printers employing Fused Deposition Modeling (FDM) technology extrudes molten thermoplastic material through a nozzle, deposits the molten material as a cylindrical layer on a planar substrate initially or on a previously deposited thermoplastic layer at subsequent depositions, and solidifies in situ. This process repeats itself until a three-dimensional structure was formed. 3D printers employing Liquid Jet technology ejects liquid through a nozzle to deposit a layer of material. The liquid is cured by ultraviolet light. The process of ejection and curing repeats itself to form a three-dimensional object. The manufacturing process is known as 3D printing or additive manufacturing.

Specimens of rectangular plate shape were printed at dimensions of 50.8 mm in length, 12.7 mm in width, and 3.2 mm in height. They were printed at a combination of raster angles of 0 degree, 45 degrees, and 90 degrees, and orientations of flat and up. Figure 5 shows 3D printed specimens at various raster angles and orientations. Solid and sparse structures were printed by Stratasys Fortus 450mc printer. Structures with 10% fill and 50% fill were printed by MakerBot Replicator Z18 printer. Two sets of 10% and 50% filled structures were produced for testing repeatability. Specimen identifications with print orientation, raster angle, and structure are listed in Table 2.

Figure 1. Stratasys Fortus 450mc Printer

Figure 2. Stratasys J750 Digital Anatomy Printer

Figure 3. Stratasys Objet30 Printer

Figure 4. MakerBot Replicator Z18 Printer

Figure 5. 3D Printed Specimens

Table 2. Specimen Identification

Specimen Identification	3D Printer	Orientation	Raster Angle, degree	Note
Objet30_00F	Stratasys Objet30	Flat	0	Liquid raw material
Objet30_00U	Stratasys Objet30	Up	0	Liquid raw material
Objet30_45F	Stratasys Objet30	Flat	45	Liquid raw material
Objet30_45U	Stratasys Objet30	Up	45	Liquid raw material
Objet30_90F	Stratasys Objet30	Flat	90	Liquid raw material
Objet30_90U	Stratasys Objet30	Up	90	Liquid raw material
J750_00F	Stratasys J750	Flat	0	Liquid raw material
J750_00U	Stratasys J750	Up	0	Liquid raw material
J750_45F	Stratasys J750	Flat	45	Liquid raw material
J750_45U	Stratasys J750	Up	45	Liquid raw material
J750_90F	Stratasys J750	Flat	90	Liquid raw material
J750_90U	Stratasys J750	Up	90	Liquid raw material
Fortus450_Solid_00F	Stratasys Fortus 450mc	Flat	0	Solid Structure
Fortus450_Solid_00U	Stratasys Fortus 450mc	Up	0	Solid Structure
Fortus450_Solid_45F	Stratasys Fortus 450mc	Flat	45	Solid Structure
Fortus450_Solid_45U	Stratasys Fortus 450mc	Up	45	Solid Structure
Fortus450_Solid_90F	Stratasys Fortus 450mc	Flat	90	Solid Structure

Fortus450_Solid_90U	Stratasys Fortus 450mc	Up	90	Solid Structure
Fortus450_Sparse_00F	Stratasys Fortus 450mc	Flat	0	Sparse Structure
Fortus450_Sparse_00U	Stratasys Fortus 450mc	Up	0	Sparse Structure
Fortus450_Sparse_45F	Stratasys Fortus 450mc	Flat	45	Sparse Structure
Fortus450_Sparse_45U	Stratasys Fortus 450mc	Up	45	Sparse Structure
Fortus450_Sparse_90F	Stratasys Fortus 450mc	Flat	90	Sparse Structure
Fortus450_Sparse_90U	Stratasys Fortus 450mc	Up	90	Sparse Structure
Z18_10_00F_A	MakerBot Replicator Z18	Flat	0	10% Fill Structure, First Set
Z18_10_00U_A	MakerBot Replicator Z18	Up	0	10% Fill Structure, First Set
Z18_10_45F_A	MakerBot Replicator Z18	Flat	45	10% Fill Structure, First Set
Z18_10_45U_A	MakerBot Replicator Z18	Up	45	10% Fill Structure, First Set
Z18_10_90F_A	MakerBot Replicator Z18	Flat	90	10% Fill Structure, First Set
Z18_10_90U_A	MakerBot Replicator Z18	Up	90	10% Fill Structure, First Set
Z18_10_00F_B	MakerBot Replicator Z18	Flat	0	10% Fill Structure, Second Set
Z18_10_00U_B	MakerBot Replicator Z18	Up	0	10% Fill Structure, Second Set
Z18_10_45F_B	MakerBot Replicator Z18	Flat	45	10% Fill Structure, Second Set
Z18_10_45U_B	MakerBot Replicator Z18	Up	45	10% Fill Structure, Second Set
Z18_10_90F_B	MakerBot Replicator Z18	Flat	90	10% Fill Structure, Second Set
Z18_10_90U_B	MakerBot Replicator Z18	Up	90	10% Fill Structure, Second Set
Z18_50_00F_A	MakerBot Replicator Z18	Flat	0	50% Fill Structure, First Set
Z18_50_00U_A	MakerBot Replicator Z18	Up	0	50% Fill Structure, First Set
Z18_50_45F_A	MakerBot Replicator Z18	Flat	45	50% Fill Structure, First Set
Z18_50_45U_A	MakerBot	Up	45	50% Fill Structure,

	Replicator Z18			First Set
Z18_50_90F_A	MakerBot Replicator Z18	Flat	90	50% Fill Structure, First Set
Z18_50_90U_A	MakerBot Replicator Z18	Up	90	50% Fill Structure, First Set
Z18_50_00F_B	MakerBot Replicator Z18	Flat	0	50% Fill Structure, Second Set
Z18_50_00U_B	MakerBot Replicator Z18	Up	0	50% Fill Structure, Second Set
Z18_50_45F_B	MakerBot Replicator Z18	Flat	45	50% Fill Structure, Second Set
Z18_50_45U_B	MakerBot Replicator Z18	Up	45	50% Fill Structure, Second Set
Z18_50_90F_B	MakerBot Replicator Z18	Flat	90	50% Fill Structure, Second Set
Z18_50_90U_B	MakerBot Replicator Z18	Up	90	50% Fill Structure, Second Set

A universal testing machine, PASCO model ME-8244 Comprehensive Materials Testing System with 7100 Newton capacity (Figure 6), was utilized to measure the mechanical properties of thermoplastics. The test stand is showed in Figure 7. A specimen was mounted on the machine and subjected to a 3-point flexural bending test (Figure 8). Testing procedure was carried out according to ASTM Standard D790-17: Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. The specimen was pressed at three points until failure (Figure 9) or at maximum bending. Applied force in Newton and specimen deflection position in millimeter were continuously measured during the test. The data were recorded at 0.2 second intervals. Typical flexural test graph is showed in Figure 10. Specimens after the flexural test are showed in Figure 11.

Figure 6. PASCO model ME-8244 Universal Testing Machine

Figure 7. Test Stand

Figure 8. Specimen Mounted on Test Stand

Figure 9. Specimen Failure During Testing

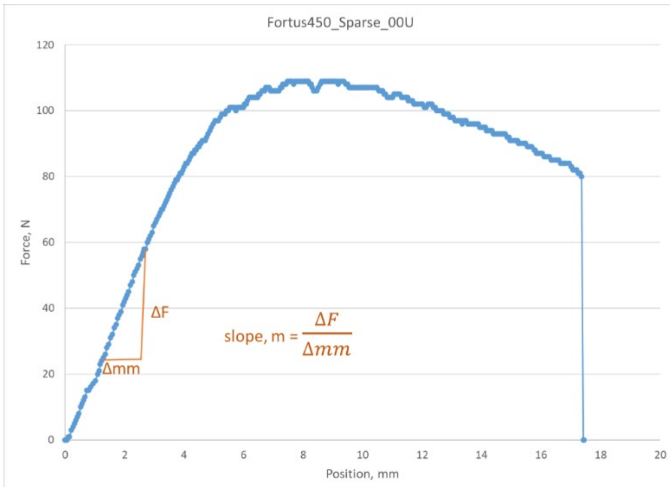

Figure 10. Load-Deflection Curve of Fortus450_Sparse_00U Experiment

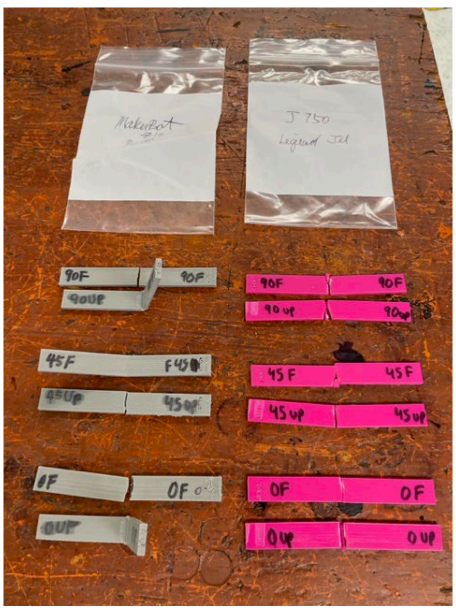

Figure 11. Specimens after Flexural Test

4. Results and Discussion

Flexural stress is determined according to the equation:

$$\sigma = \frac{3PL}{2bd^2}$$

σ = flexural stress, MPa
P = load at a given point on the load-deflection curve, N
L = support span, mm (50.8 mm for the experiment)
b = width of beam tested, mm (12.7 mm for the experiment)
d = depth of beam tested, mm (3.2 mm for the experiment)

Flexural strain is determined according to the equation:

$$\varepsilon = \frac{6Dd}{L^2}$$

ε = flexural strain, mm/mm
D = maximum defection of the center of the beam, mm
L = support span, mm (50.8 mm for the experiment)
d = depth of beam tested, mm (3.2 mm for the experiment)

Modulus of elasticity is determined according to the equation:

$$E = \frac{L^3 m}{4bd^3}$$

E = modulus of elasticity in bending, MPa
L = support span, mm (50.8 mm for the experiment)
b = width of beam tested, mm (12.7 mm for the experiment)
d = depth of beam tested, mm (3.2 mm for the experiment)
m = slope of the tangent to the initial straight-line portion of the load-deflection curve, N.mm of deflection

Flexural strength is determined as the maximum stress of a stress-strain curve. Typical stress-strain curve of Fortus450 Sparse_00U is depicted in Figure 12.

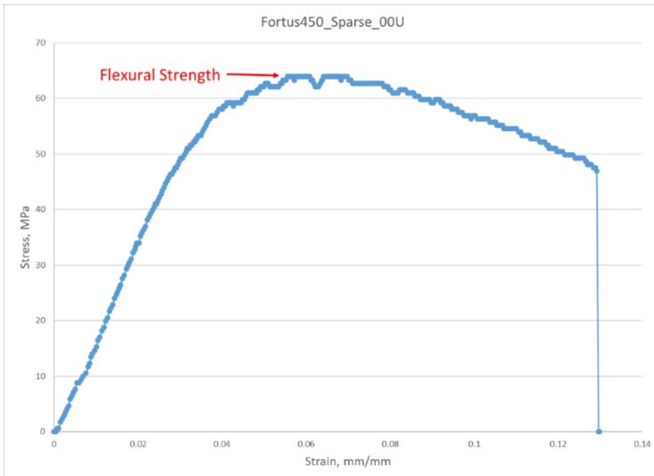

Figure 12. Stress-Strain Curve of Fortus450_Sparse_00U specimen

4.1 Modulus of Elasticity

Modulus of elasticity of all specimens are shown in Figure 13 and 14. Specimens printed by Fortus 450mc exhibit the lowest modulus of elasticity among all specimens (Figure 13 and 14). Modulus of elasticity of specimens printed by Z18 printer are generally high among all specimens.

Highest modulus of elasticity is generally observed at the 45-degree raster angle (Table 3 and Figure 14), except for solid structure specimens printed by Fortus 450mc. The up orientation generally has the maximum modulus of elasticity, except the specimens of Objet30_45F and Fortus450_Solid_90F. The maximum modulus elasticity of 2985 MPa is determined at Objet30_45F, 2866 MPa at J750_45U, 1926 MPa at Fortus450_Solid_90F, 1901 MPa at Fortus450_Sparse_45U, 2924 MPa at Z18_10_45U_A, 3072 MPa at Z18_10_45U_B, 3392 MPa at Z18_50_45U_A, and 3417 MPa at Z18_50_45U_B (Table 3 and Figure 14).

Table 3: Maximum Modulus of Elasticity

Specimen ID	Raster Angle, degree	Orientation	Internal Structure	Maximum Modulus of Elasticity, MPa
Objet30_45F	45	Flat	Solid	2985
J750_45U	45	Up	Solid	2866
Fortus450_Solid_90F	90	Flat	Solid	1926
Fortus450_Sparse_45U	45	Up	Sparse	1901
Z18_10_45U_A	45	Up	10 % Fill (first dataset)	2924
Z18_10_45U_B	45	Up	10% Fill (second dataset)	3072
Z18_50_45U_A	45	Up	50% Fill (first dataset)	3392
Z18_50_45U_B	45	Up	50% Fill (second dataset)	3417

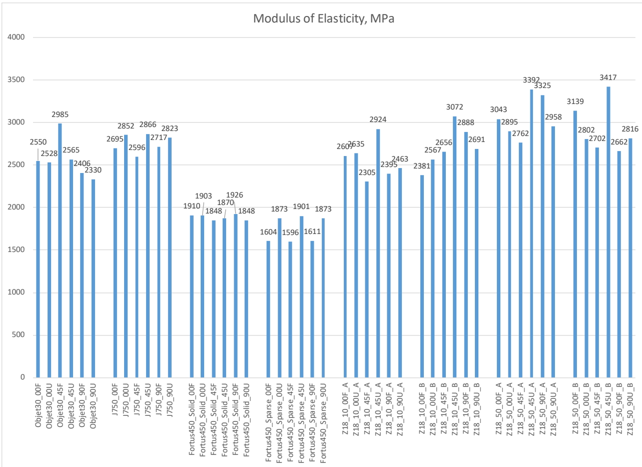

Figure 13. Modulus of Elasticity of All Specimens

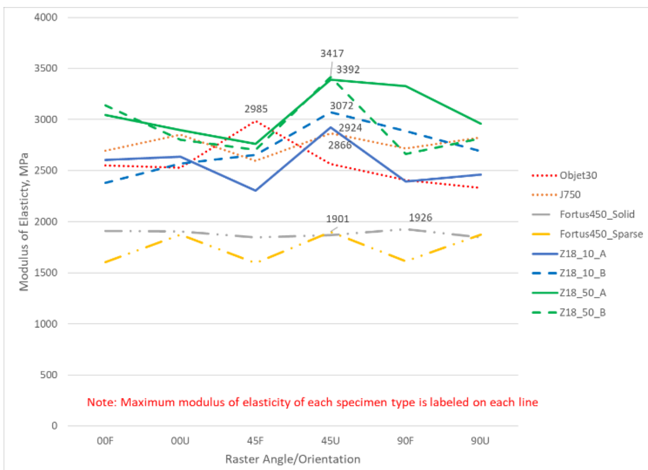

Figure 14. Modulus of Elasticity of All Specimens

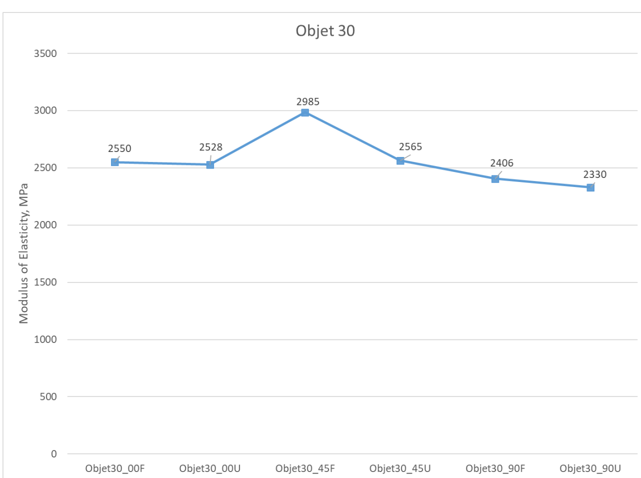

Figure 15. Modulus of Elasticity of Objet30 Specimens

Modulus of elasticity of Objet30 specimens varies from 2330 MPa to 2985 MPa (Figure 15). The highest modulus of elasticity at 2985 MPa is noted in the specimen printed at 45-degree raster angle/flat orientation.

Modulus of elasticity of specimens printed by J750 printer are generally higher than those of specimens printed by Objet30 (Figure 16). Their values range from 2596 MPa to 2866 MPa. These two printers employ liquid raw materials. The highest modulus of elasticity at 2866 MPa and the lowest modulus of elasticity at 2596 MPa are found at 45-degree raster angle/up orientation and 45-degree raster angle/flat orientation, respectively.

In comparison with the modulus of elasticity of Objet30 specimens, the values of J750 are generally higher by 145 MPa to 493 MPa (Figure 17). The J750 specimen at 45-degree/flat orientation is the only specimen that has the modulus of elasticity at 389 MPa lower than that of the Objet30 (Figure 17).

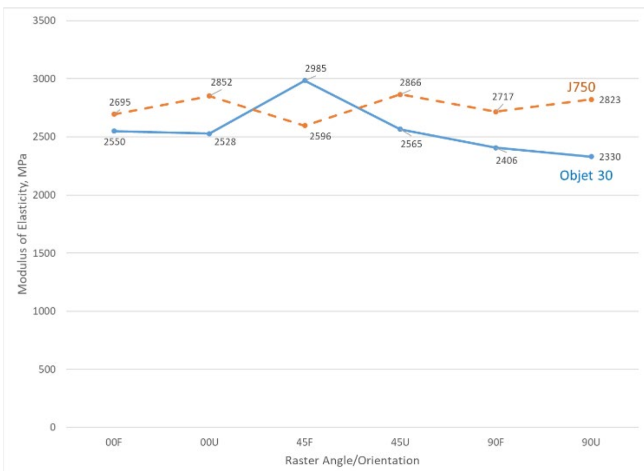

Figure 16. Modulus of Elasticity of J750 and Objet30 Specimens

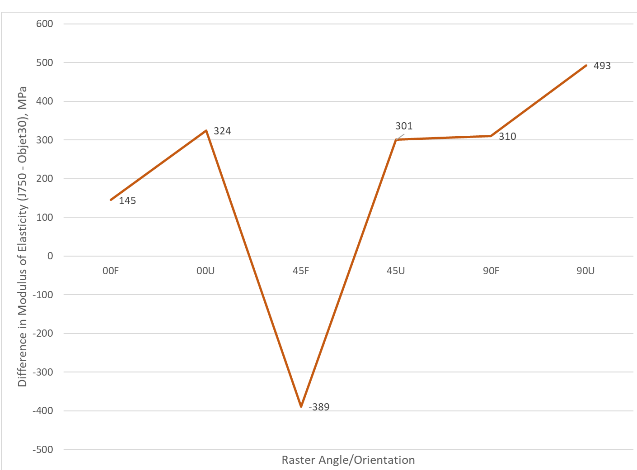

Figure 17. Modulus of Elasticity of J750 and Objet30 Specimens

Modulus of elasticity of Fortus 450mc solid specimens ranges from 1848 MPa to 1926 MPa (Figure 18). The values are relatively constant in all raster angles and orientations. The maximum variation among all values is 78 MPa.

Larger variations in modulus of elasticity are found in Fortus 450mc sparse specimens with the maximum difference in value at 305 MPa (Figure 18). The values of modulus of elasticity range from 1596 MPa to 1901 MPa. There is a distinct pattern that specimens printed in up position are stiffer than those printed in flat orientation in all three raster angles. Modulus of elasticity of up positon are higher than that of the flat position by 269 MPa, 305 MPa, and 262 MPa, at 0-degree, 45-degree, and 90-degree raster angle, respectively. Modulus of elasticity of up position remains relatively constant at values of 1873 MPa to 1901 MPa. Modulus of elasticity of flat position stays approximately at the same level from 1596 MPa to 1611 MPa.

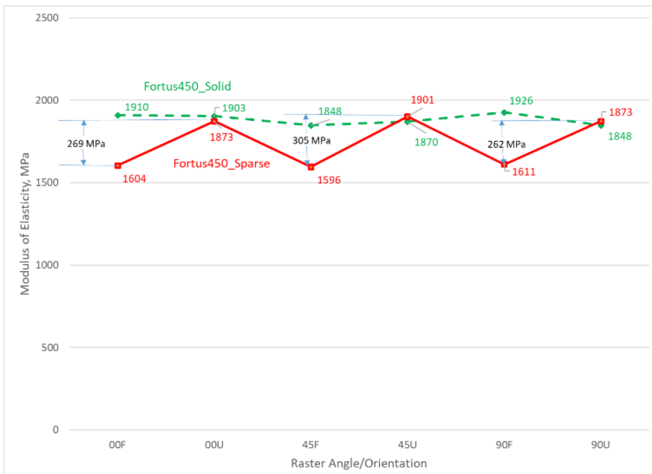

Figure 18. Modulus of Elasticity of Fortus450_Solid and Fortus450_Sparse Specimens

Modulus of elasticity of Z18 at 50% fill are higher than that of Z18 at 10% fill (Figure 19). Modulus of elasticity of Z18 at 50% fill of the two datasets varies from 2662 MPa to 3417 MPa; while that of Z18 at 10% fill of the two datasets ranges from 2305 MPa to 3072 MPa.

The highest modulus of elasticity of Z18 at 10% specimen (Figure 19) is identified at specimen printed 45-degree raster angle/up orientation in both datasets of specimens; dataset A at 2924 MPa and dataset B at 3072 MPa. The same observation is found in Z18 at 50% fill specimens (Figure 19). The highest modulus of elasticity is observed at 45-degree raster angle/up orientation. Their values are 3392 MPa in dataset A and 3417 MPa in dataset B.

Modulus of elasticity of two datasets of 10% fill specimens printed by Z18 printer are compared in Figure 19. Modulus of elasticity of the two sets of data are in general agreement with each other. Differences in modulus of elasticity of 00F, 00U, 45F, 45U, 90F, and 90U specimens are 226 MPa, 68 MPa, 351 MPa, 148 MPa, 493 MPa, and 228 MPa, respectively. The largest variation is noted in at 90-degree raster angle/flat orientation.

Modulus of elasticity of two sets of 50% fill specimens printed by Z18 printer are compared in Figure 19. Five out of six pairs of datasets have excellent agreements with each other. Differences in modulus of elasticity of 00F, 00U, 45F, 45U, 90F, and 90U specimens are 96 MPa, 93 MPa, 60 MPa, 25 MPa, 663 MPa, and 142 MPa, respectively. Based on the data of the datasets, the experiments are repeatable.

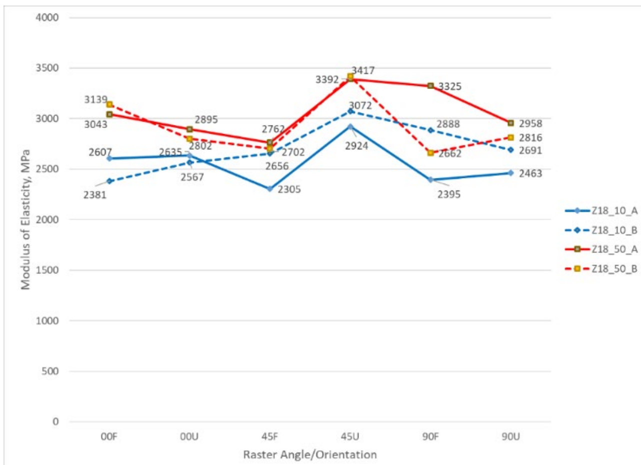

Figure 19. Modulus of Elasticity of Z18 Specimens

4.2 Flexural Strength

Flexural strength of all specimens is depicted in Figure 20 and 21. High flexural strength is found in specimens printed by Liquid Jet technology in Objet30 and J750 printers (Table 4 and Figure 21)). Flexural strength of Objet30 specimens ranges from 92.58 MPa to 109.57 MPa, that of J750 specimens varies from 103.71 MPa to 111.33 MPa (Figure 22). Low flexural strength is noted in specimens printed by Fortus 450mc printer (Figure 20 and 21). The sparse structure of Fortus 450mc specimens exhibits the lowest flexural strength ranging from 46.29 MPa to 63.87 MPa.

Specimens produced by Liquid Jet technology in Objet30 and J750 printers exhibit the highest flexural strength among all specimens (Table 4 and Figure 21). Variations of flexural strength in specimens printed by the two printers are low (Figure 22). The highest flexural strength of J750 specimen of 111.33 MPa is found at 90-degree raster angle/flat orientation, whereas that of Objet30 of 109.57 MPa at 45-degree raster angle/flat orientation.

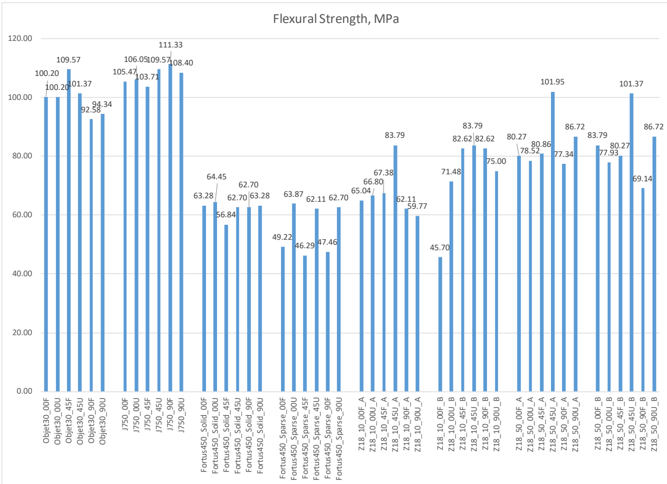

Figure 20. Flexural Strength of all Specimens

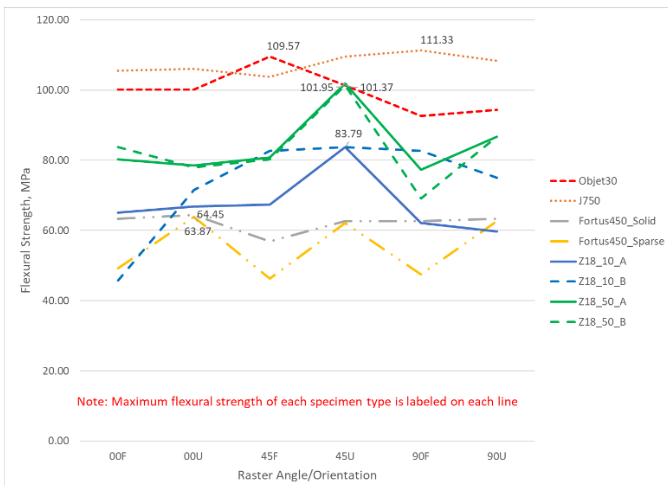

Figure 21. Flexural Strength of All Specimens

Table 4: Maximum Flexural Strength

Specimen ID	Raster Angle, degree	Orientation	Internal Structure	Maximum Flexural Strength, MPa
Objet30_45F	45	Flat	Solid	109.57
J750_90F	90	Flat	Solid	111.33
Fortus450_Solid_00U	0	Up	Solid	64.45
Fortus450_Sparse_00U	0	Up	Sparse	63.87
Z18_10_45U_A	45	Up	10 % Fill (first dataset)	83.79
Z18_10_45U_B	45	Up	10% Fill (second dataset)	83.79
Z18_50_45U_A	45	Up	50% Fill (first dataset)	101.95
Z18_50_45U_B	45	Up	50% Fill (second dataset)	101.37

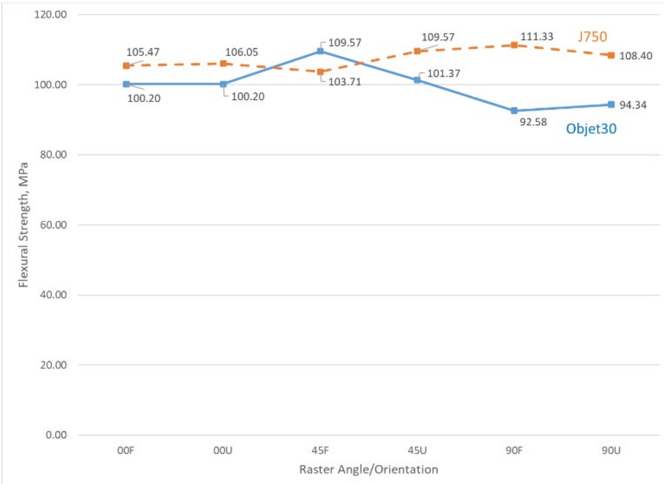

Figure 22. Flexural Strength of J750 and Objet30 Specimens

Lowest flexural strength is generally noted in specimens with sparse structure printed by Fortus 450mc printer (Figure 21 and 23). Flexural strengths of solid structure specimens vary from 56.84 MPa to 64.45 MPa. Raster angle and orientation are not dominant factors that affect flexural strength in solid structure specimens. Up orientation is the major factor that provides the highest flexural strength in sparse structure specimens in all three raster angles. Flexural strength of sparse structure at up orientation are 63.87 MPa, 62.11 MPa, and 62.70 MPa at 0 degree, 45 degrees, and 90 degrees, respectively. Lower flexural strength of 49.22 MPa, 46.29 MPa, and 47.46 MPa are found at sparse structure of flat orientation at 0 degree, 45 degrees, and 90 degrees, respectively.

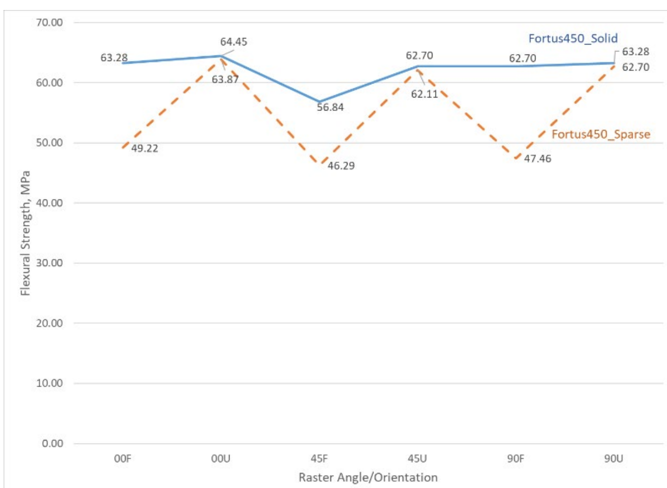

Figure 23. Flexural Strength of Fortus450 Specimens

Figure 24 depicts the flexural strength of Z18 specimens. A good agreement is found in two datasets of 50% fill specimens. Difference of 3.52 MPa is noted between the two datasets at 00F, 0.59 MPa at 00U, 0.59 MPa at 45F, 0.58 MPa at 45U, 8.23 MPa at 90F, and 0 MPa at 90U (Figure 25). Larger difference in flexural strength is determined in the two datasets of 10% fill specimens. The difference in value varies from -20.51 MPa to 19.34 MPa (Figure 26).

The combination of 45-degree raster angle/up orientation produces the highest flexural strength of Z18 specimens in both 10% fill and 50% fill (Figure 24). The highest flexural strength values of the two datasets of Z18 with 10% fill match perfectly with each other at 83.79 MPa. The same observation is found in the two datasets of Z18 with 50% fill with 101.95 MPa in dataset A and 101.37 MPa in dataset B (Figure 24).

Flexural strength of Z18 with 50% fill is generally higher than that with 10% fill (Figure 24). By comparison of the dataset A of the two fill structures, flexural strength of 50% fill structure is greater than that of 10% fill structure by 11.72 MPa to 26.95 MPa (Figure 27).

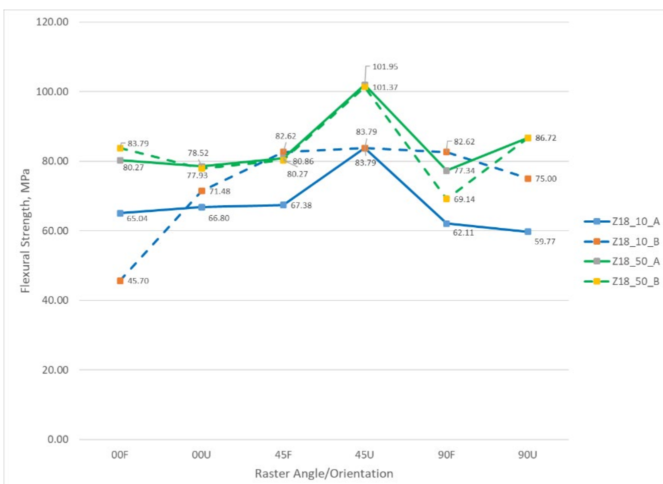

Figure 24. Flexural Strength of Z18 Specimens

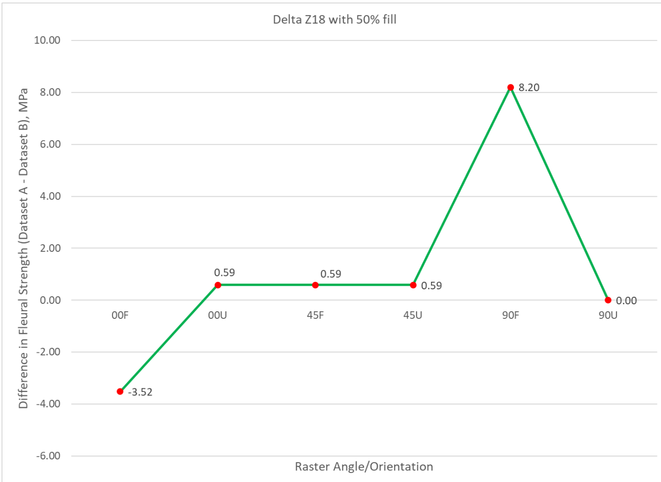

Figure 25. Comparison of Flexural Strength of Z18 Specimen Datasets with 50% Fill

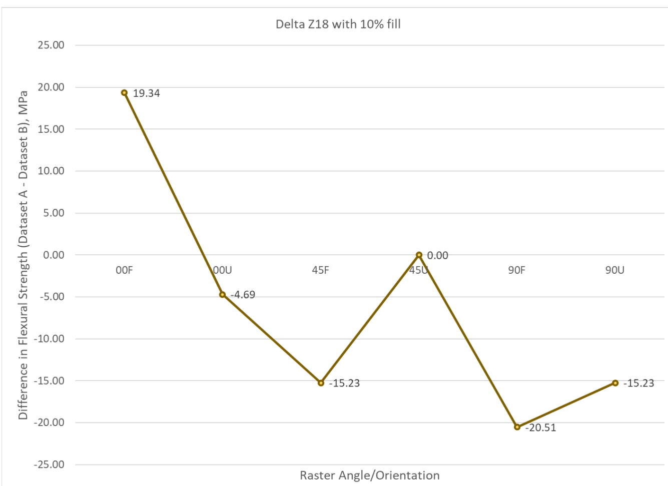

Figure 26. Comparison of Flexural Strength of Z18 Specimen Datasets with 10% Fill

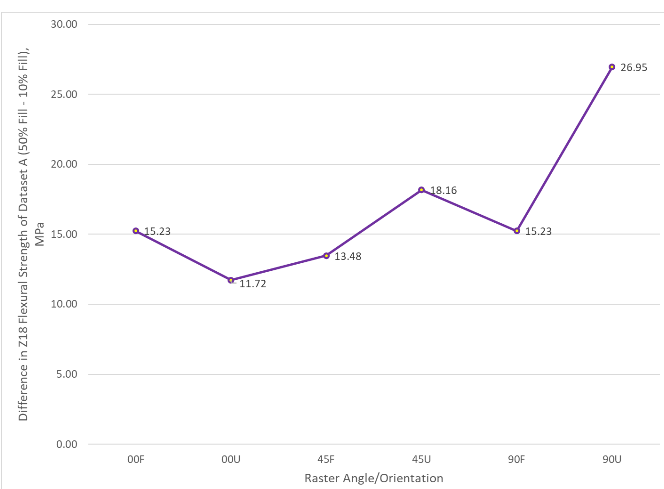

Figure 27. Difference in Flexural Strength of Z18 Dataset A Specimens

5. Conclusion

Lowest modulus of elasticity is found in Fortus450 specimens. Highest modulus of elasticity is found in Z18 with 50% fill specimens. The two printers employ the 3D printing technology of Fused Deposition Modeling (FDM). Z18 specimens are therefore stiffer than Fortus450 specimens. Moderate modulus of elasticity is determined in Objet30 and J750 specimens printed by the 3D printing technology of Liquid Jet.

Higher the fill percentage of a 3D printed structure higher is structural stiffness, as it is evident in the modulus of elasticity of Z18 with 50% fill and that of Z18 with 10% fill and in the solid and sparse structure of Fortus450 specimens.

45-degree raster angle/up orientation produced the highest modulus of elasticity in specimens printed by Fused Deposition Modeling. 45-degree raster angle also create the highest modulus of elasticity in specimens printed by Liquid Jet; however, 45-degree raster angle/flat yields the maximum modulus of elasticity of 2985 MPa in Objet30 and 45-degree raster angle/up orientation brings about the maximum modulus of elasticity o 2924 MPa in J750.

The lowest flexural strength is noted in Fortus450 specimens. The highest flexural strength is discovered generally in J750 specimens. Liquid Jet technology creates materials that are stronger in bending than those produced by Fused Deposition Modeling. Z18 printer using Fused Deposition Modeling manufactures materials with moderate flexural strength.

0-degree raster angle/up orientation produced the highest flexural strength in Fortus450 specimens. 45-degree raster angle/up orientation created the highest flexural strength in Z18 specimens. Liquid Jet technology brings about high flexural strength in Objet30 and J750 specimens at various raster angle/orientation. The maximum flexural strength is noted at 45-degree/flat orientation, while that at 90-degree raster angle/flat orientation in Liquid Jet specimens.

Modulus of elasticity of Fortus 450mc solid specimens are relatively constant in all raster angles and orientations; however, sparse specimens printed in up position are stiffer than those printed in flat orientation in all three raster angles.

Structures with higher percentage of fill produce higher flexural strength as it is observed in the performance of Z18 with 50% fill and 10% fill and Fortus450 with solid and sparse structures.

Modulus of elasticity and flexural strength data of two datasets of Z18 demonstrated repeatability of the experiment.

Objet30 specimens produced from liquid raw materials exhibit a similar pattern in modulus of elasticity and flexural strength in respect to raster angle and orientation (Figure 16 and 22). The highest modulus of elasticity of 2985 MPa and flexural strength of 109.57 MPa are both found at 45-degree raster angle/flat orientation. The lowest modulus of elasticity and flexural strength are determined at 90-degree raster angle/flat orientation or 90-degree raster angle/up orientation.

J750 specimens also demonstrate a similar pattern modulus of elasticity and flexural strength in respect to raster angle and orientation (Figure 16 and 22). The pattern of J750 behaves reversely as a mirror image of that of Objet30 in both modulus of elasticity and flexural strength. Maximum modulus of elasticity at 2985 MPa and maximum flexural strength at 109.57 MPa of Objet30 specimens are both found at 45-degree raster angle/flat orientation. Minimum modulus of elasticity at 2596 MPa and minimum flexural strength at 103.71 MPa of J750 specimens are simultaneously determined at the same 45-degree raster angle/flat orientation.

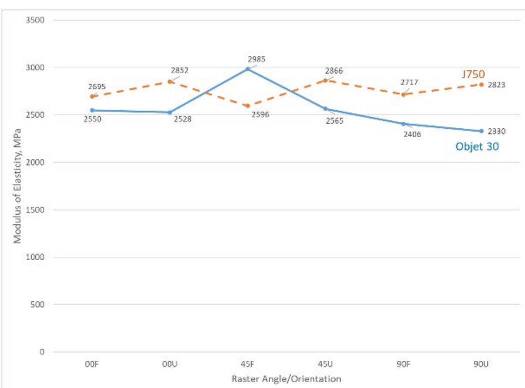

Figure 16. Modulus of Elasticity of J750 and Objet30 Specimens

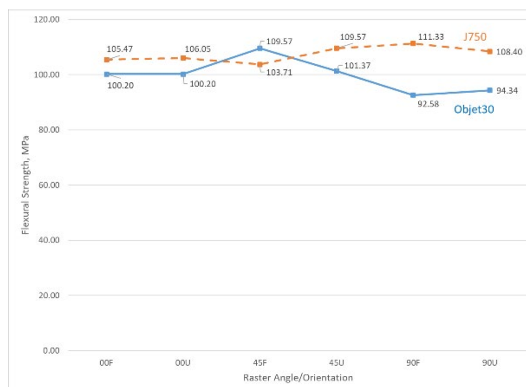

Figure 22. Flexural Strength of J750 and Objet30 Specimens

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