# Ultimate Tensile Strengths of 3D Printed Carbon-fiber Reinforced Thermoplastics in Liquid Nitrogen

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## Introduction: Taking Carbon-fiber to Cryogenic Conditions

Polymers currently offer superior light-weighting design potential compared to conventional metal components due to lower thermal conductivity, density, and often reduced associated manufacturing costs. However, the ultimate strength of these components is often inferior to conventional materials. Embedding carbonous additives, including chipped strand and graphene sheets into 3D printable polymers, is one promising method for increasing strength of the bulk material. This work performs ultimate tensile strength testing of 3D printed thermoplastics immersed in liquid nitrogen at approximately 77 K. Materials tested include carbon-fiber reinforced PETG and carbon-fiber reinforced Amphora AM1800 filament.

## Materials and Methods

Test specimens are printed using a Felix Pro 1 3D printer on a bed made of Mylar, with coatings of hairspray between prints to improve adhesion between the polymer and the bed. Five specimens of carbon-fiber reinforced polyethylene terephthalate glycol (PETG) and carbon-fiber reinforced Amphora AM1800 filament (Amphora) were printed in an XY orientation. Specimen geometry is tested in accordance with the ASTM D638 Type 1 sample standard. Figure 1 shows the specimen dimensions and the extensometer used.

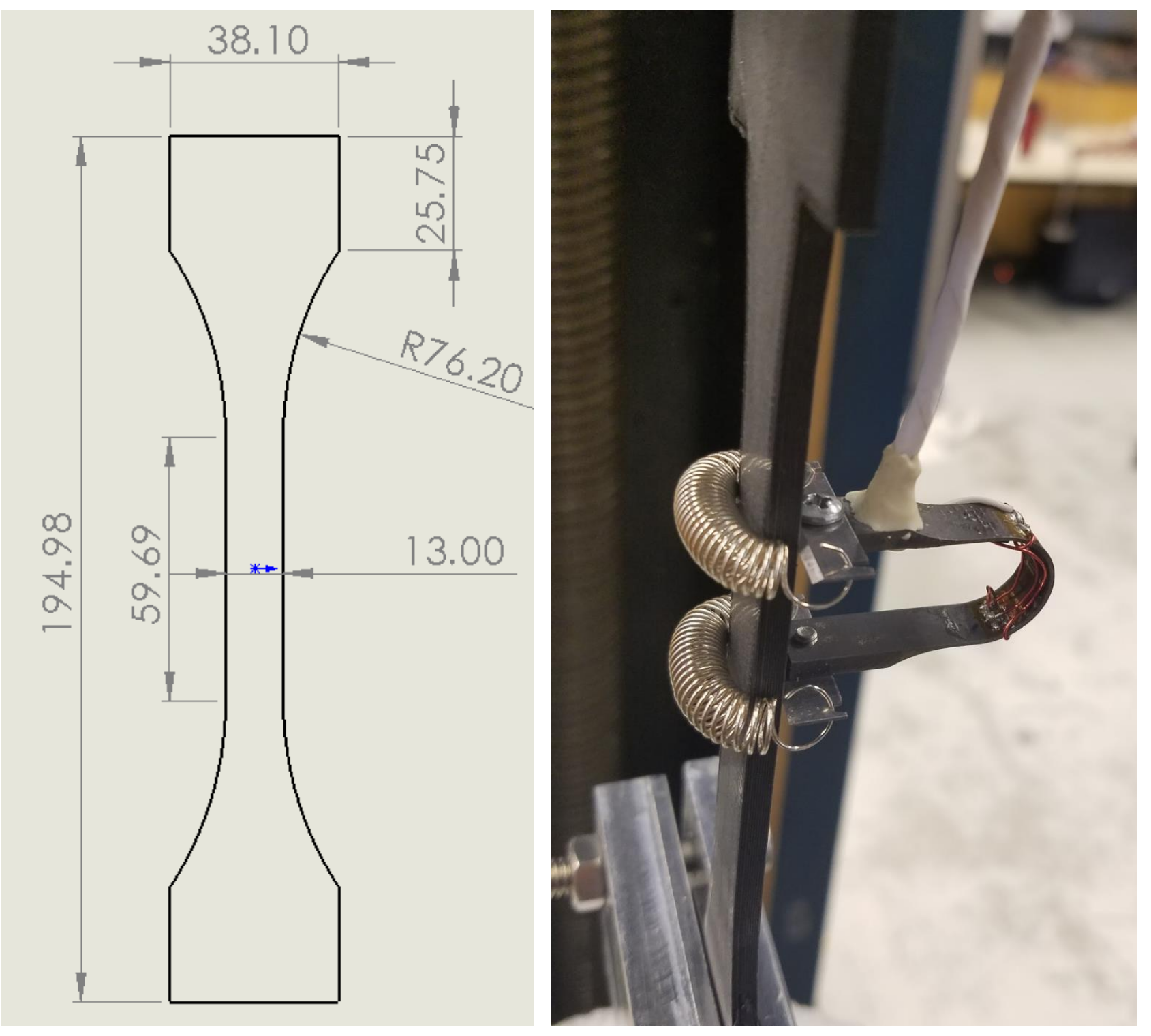

**Figure 1.** Testing sample dimensions (left) and linear extensometer setup on sample (right). All dimensions are in millimeters.

A U-shaped extensometer with knife-blade edges was used to measure the strain on the specimens. Manufacturer data for the error in the extensometer was not available. The extensometer uncertainty was measured through calibration between room-temperature and 77 K. A zero-strain measurement was taken with the extensometer for each sample prior to cooling with zero load. A cryostat was designed that allowed for full submersion of the specimen and clamps in liquid nitrogen. Figure 2 shows the load frame and the experimental setup diagram.

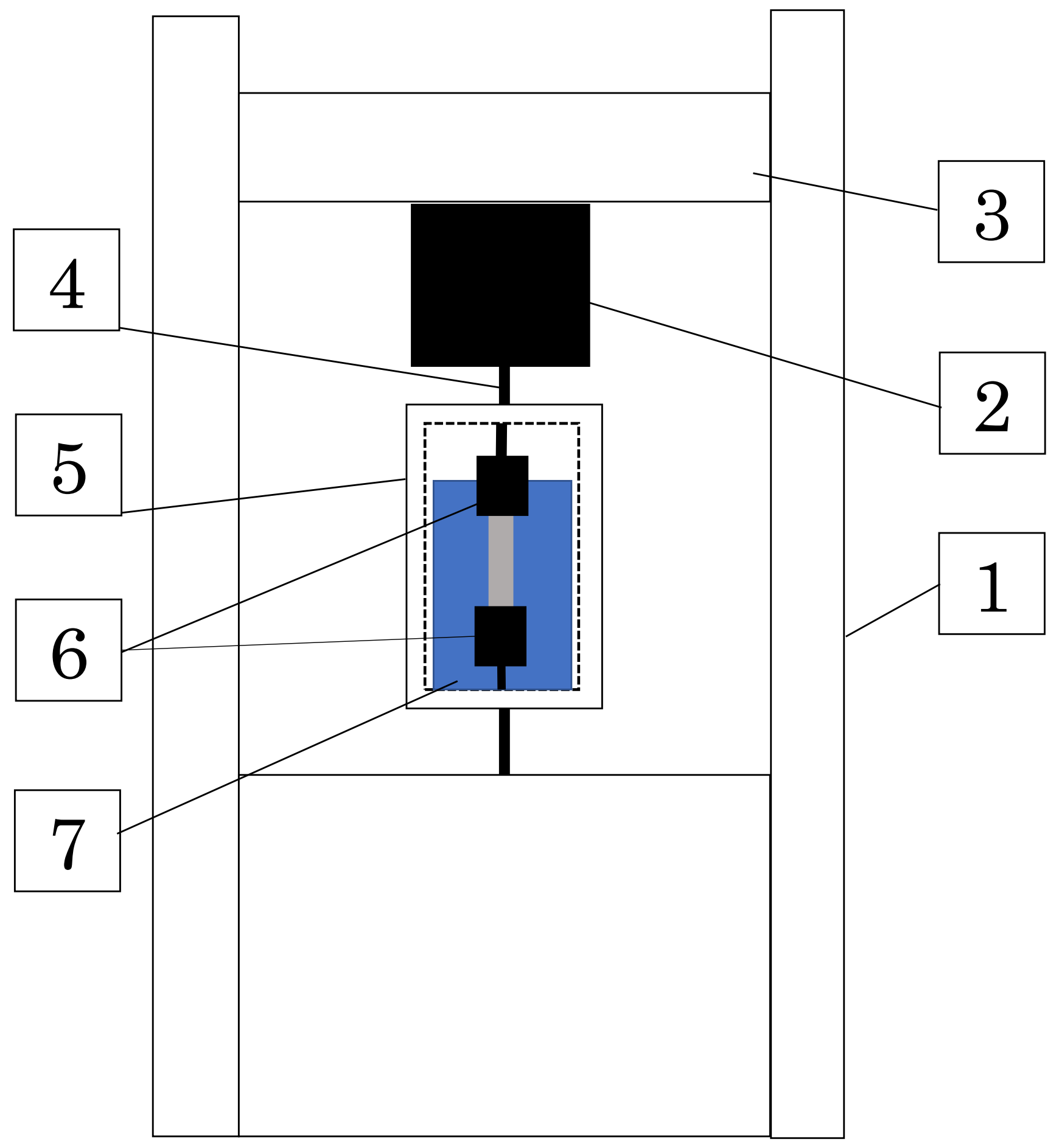

**Figure 2.** Experimental setup diagram for tensile testing in liquid nitrogen.

| Component | |
|---|---|
| 1 | Frame |
| 2 | Load cell |
| 3 | Crosshead |
| 4 | Extension rod |
| 5 | Cryostat |
| 6 | Grips |
| 7 | Liquid nitrogen |

## Results and Discussion

The ultimate tensile strength, percent elongation at fracture, and modulus of elasticity for the PETG were calculated for the XY prints. PETG showed an increase in tensile strength of 49% at 77 K compared to room temperature. This is represented by an increase from 55.5 MPa to 82.8 MPa. The PETG showed a decrease of 0.659 percent elongation at fracture when cooled, representing a decrease from 2.5% to 1.84%.The modulus of elasticity of the PETG increased by 43.2% from 4928 MPa to 7057 MPa.

Similar testing to the PETG specimens was performed for the Amphora. Only ultimate tensile strength data could be collected for the Amphora specimens. The tests performed with this material showed an average maximum tensile strength of 53.3 MPa under the same testing conditions of the PETG filament. This was a decrease in tensile strength of 29.9% from a room temperature ultimate strength of 76.0 MPa to 53.3 MPa. Table 1 lists the available ultimate tensile strengths and elastic moduli of the tested materials at room-temperature and 77 K.

**Table 1.** 77 K ultimate tensile strength and modulus of elasticity. Manufacturer room temperature values given in parentheses for reference.

| Material | Temperature (K) | Ultimate Stress (MPa) | Elastic Modulus (GPa) |
|---|---|---|---|
| **Carbon Fiber Reinforced PETG** | (295)<br>77 | (55.5)<br>82.8<br>±4.26 | (4.928)<br>7.057<br>±0.49 |
| **Carbon Fiber Reinforced Amphora AM1800** | (295)<br>77 | (76)<br>53.3<br>±1.85 | -[a]<br>-[b] |

[a] Modulus of elasticity not available from the manufacturer.

[b] Modulus measurements not taken.

It should be noted that there were changes and limitations to the Amphora tests due to maintenance on the load frame used for the tests. The Amphora specimens were moved to testing on a separate load frame and extensometer measurements were not available for these tests. Therefore, strain values are not available or reported. Figure 4 compares the mean ultimate stress of the tested materials, with associated manufacturer data.

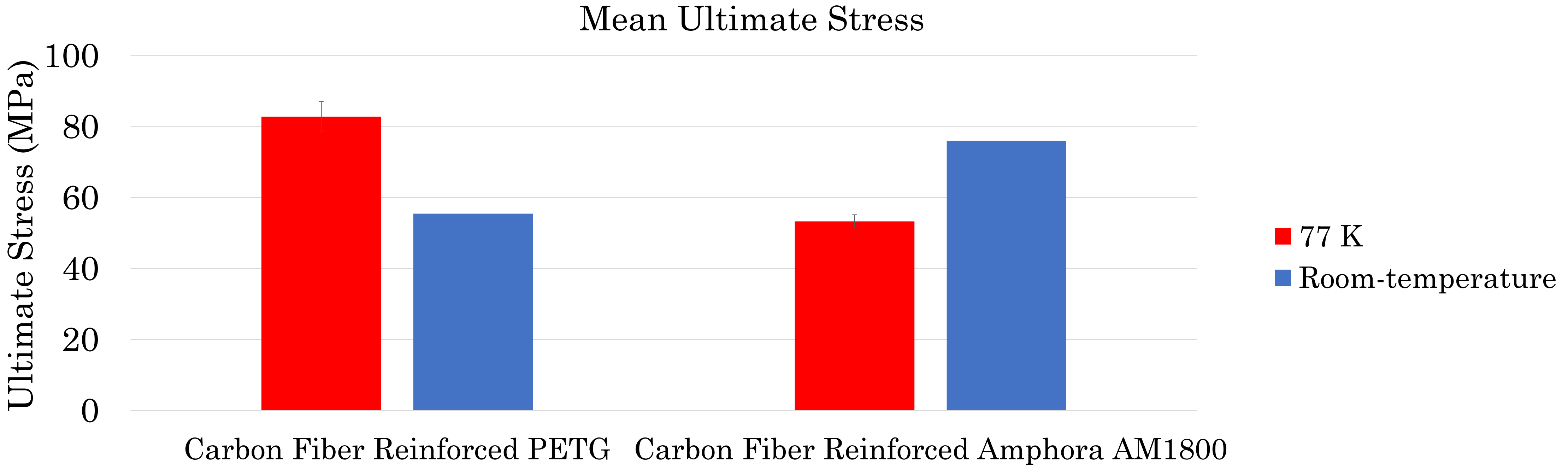

**Figure 4.** 77 K mean ultimate stress. Blue bars represent the manufacturer's data.

## Conclusion

The PETG showed results that agree with the general understanding of increasing tensile strengths as a function of decreasing temperature. The ultimate strength of the PETG increased by 49%, and the elastic modulus increased by 15.8%. The ultimate strength of the Amphora diverged from the expected trend, with a decrease of 29.9%.

## Acknowledgements

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