Phase-field modeling of fracture in additively manufactured parts

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Additive manufacturing for structural applications

For the aerospace and automotive industries, additive manufacturing offers the potential to produce highly weight-efficient multifunctional structures. Fused filament fabrication (FFF), consisting in the layer-by-layer deposition of a semi-molten polymer filament, is the most popular additive manufacturing process. However, by the nature of the process itself, FFF produces parts with weak interlayers. Consequently, FFF parts present a complex anisotropic tensile and fracture behavior. For the aerospace industry to use FFF produced load-bearing structures, numerical models able to predict their failure must be available. Furthermore, to enable the development and the validation of accurate models, the mechanical behavior until complete failure of such parts must be characterized in-depth.

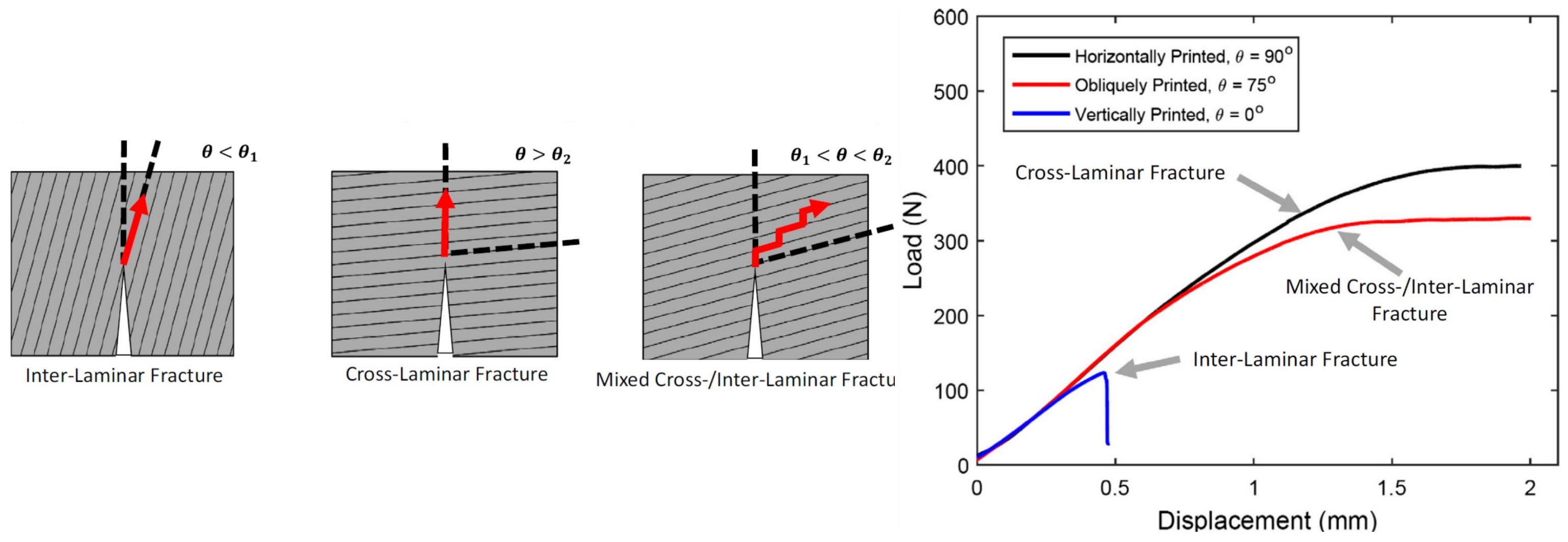

Figure 1: Fracture behavior of FFF parts under three-point bending. Modified from [1].

Objectives

The main objective of this research project is to develop and validate a phase-field fracture model (PFM) to predict the mechanical behavior of FFF parts until complete failure. The project is divided in three specific objectives:

1. Characterize the full anisotropic strength and toughness of unidirectional FFF parts.
2. Develop an implementation of a PFM and minimize its associated computational cost.
3. Propose and validate a multi-scale PFM approach able to predict the failure of FFF parts.

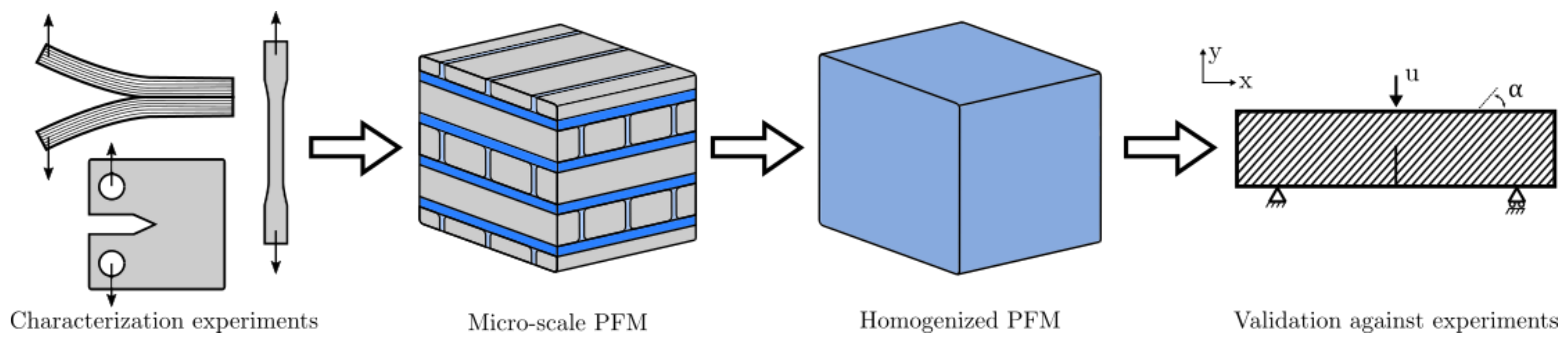

Figure 2: Multi-scale phase-field approach to fracture modeling in FFF parts.

Characterization methodology

Single Edge Notch Bending (SENB) and dogbone specimens were printed to multiple build angles (as shown in Figure 3) with Polylactic Acid (PLA) using a Raise3D Pro2 printer.

Characterization methodology (cont'd)

The specimens were submitted to the following tests:

- Three-Point Bending fracture tests, with macro-scale imaging and micro-scale digital image correlation (DIC).
- Tensile tests.
- Scanning electron microscopy (SEM).
- Differential scanning calorimetry (DSC).

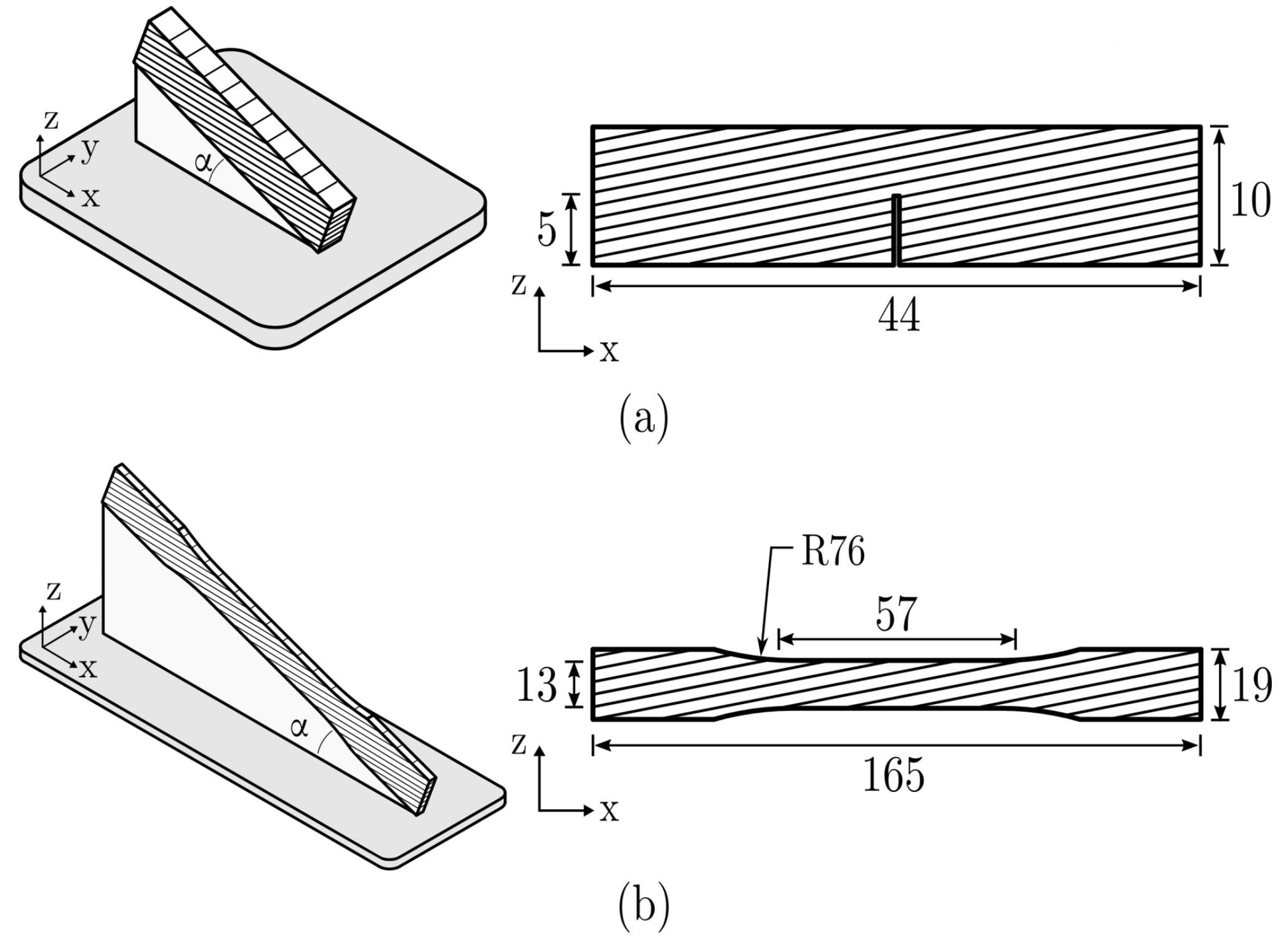

Figure 3: Geometry and build angle of the FFF PLA (a) SENB and (b) dogbone specimens.

Characterization results

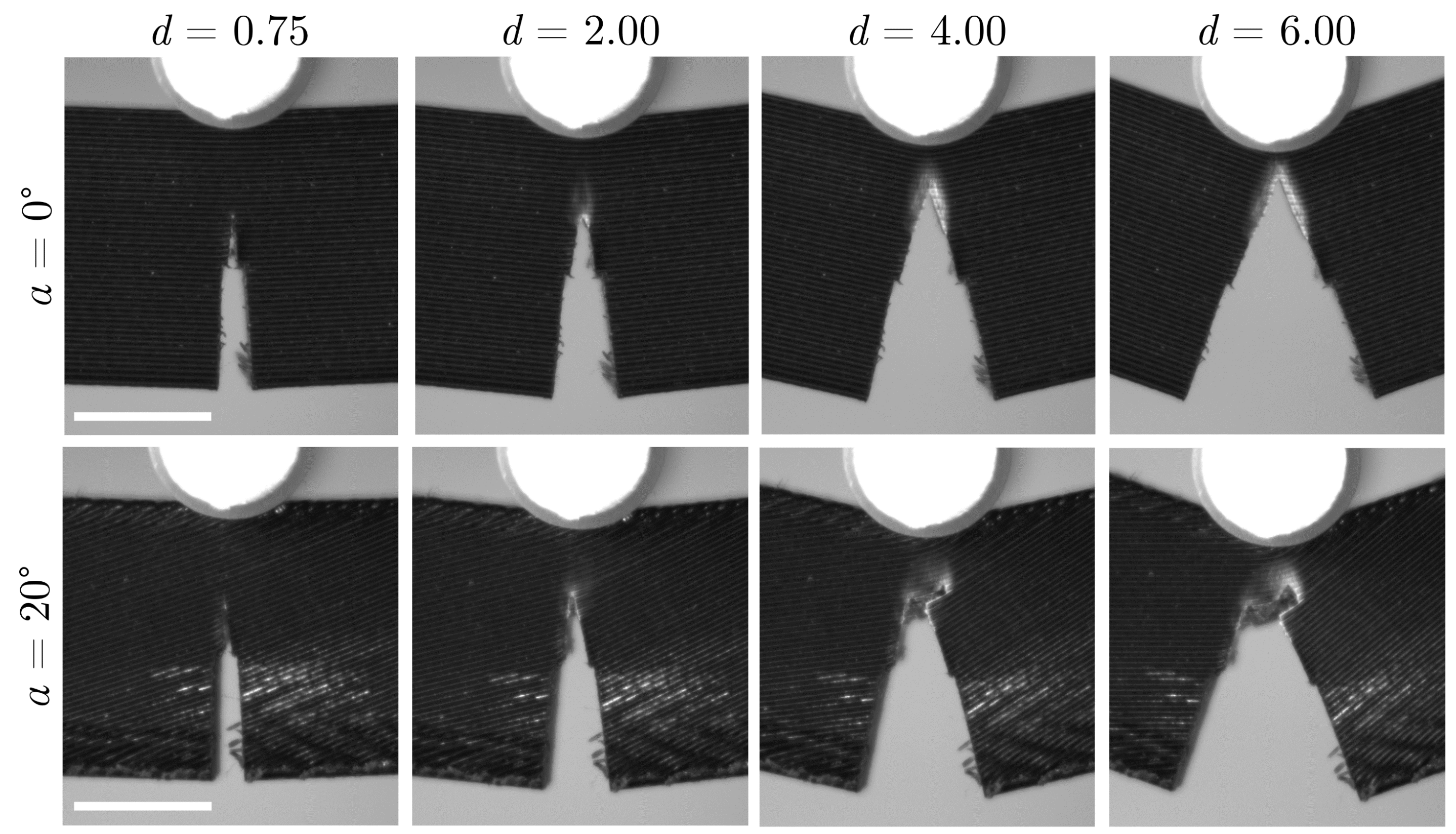

Figure 4: Fracture process under three-point bending of the SENB specimens for 0° and 20° build angles at four applied displacement. Scale bar is 5 mm.

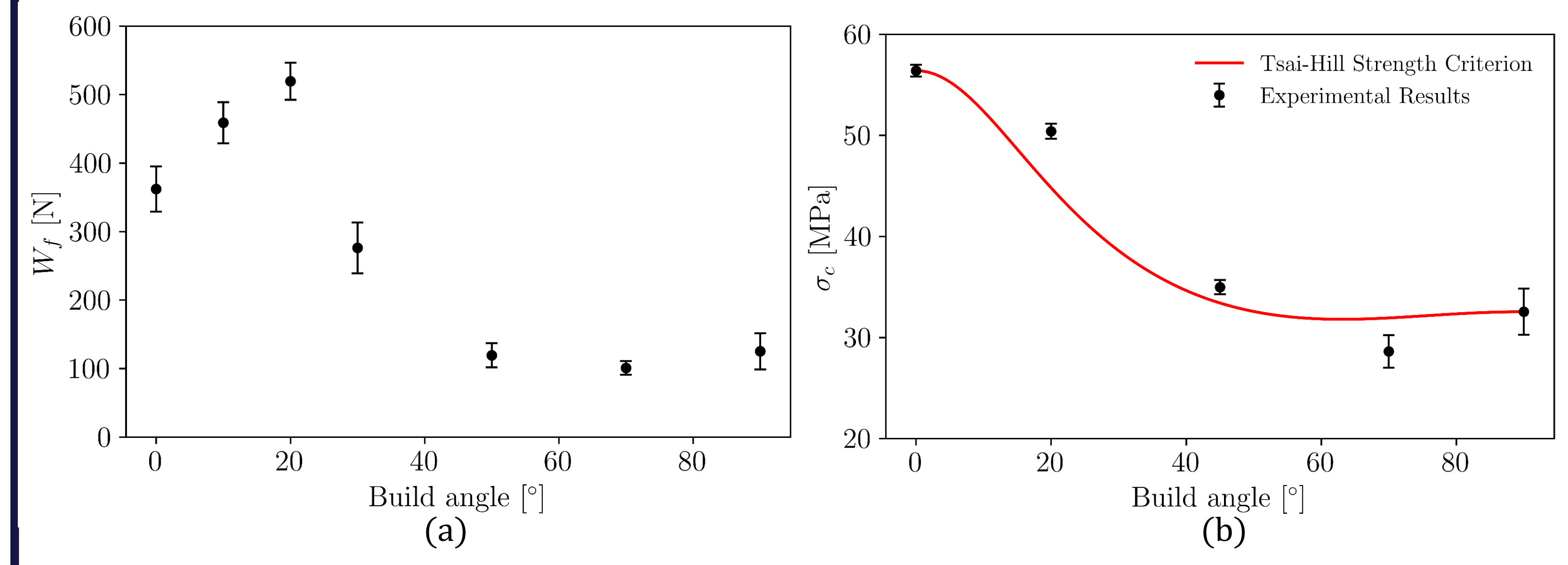

Figure 5: (a) Average work required to fracture the SENB specimens as a function of the build angle. (b) Average strength as a function of the build angle of the dogbone specimens. The bars indicate a 95% confidence interval.

Computational cost minimization methodology

A basic PFM for brittle fracture was implemented using the Julia language. The implementation uses the finite element method to minimize the energy of the cracked body:

$$\mathcal{E}(\boldsymbol{u}, d) = \int_\Omega g(d)\Psi(\boldsymbol{u})\mathrm{d}\boldsymbol{x} + G_c \int_\Omega \gamma(d, \nabla d)\mathrm{d}\boldsymbol{x}\,.$$

$g(d)$: Degradation function modulating the effective stiffness.
$\Psi(\boldsymbol{u})$: Strain energy density.
G_c: Critical energy release rate of the material.
$\gamma(d, \nabla d)$: Elliptic function approximating the crack surface.

Three different solvers were implemented and benchmarked:

- The alternating minimization solver.
- The quasi-monolithic scheme.
- A modified Newton solver with inertia correction.

The accuracy and efficiency of the three solvers were compared on four benchmarks from the phase-field fracture literature.

Computational cost minimization results

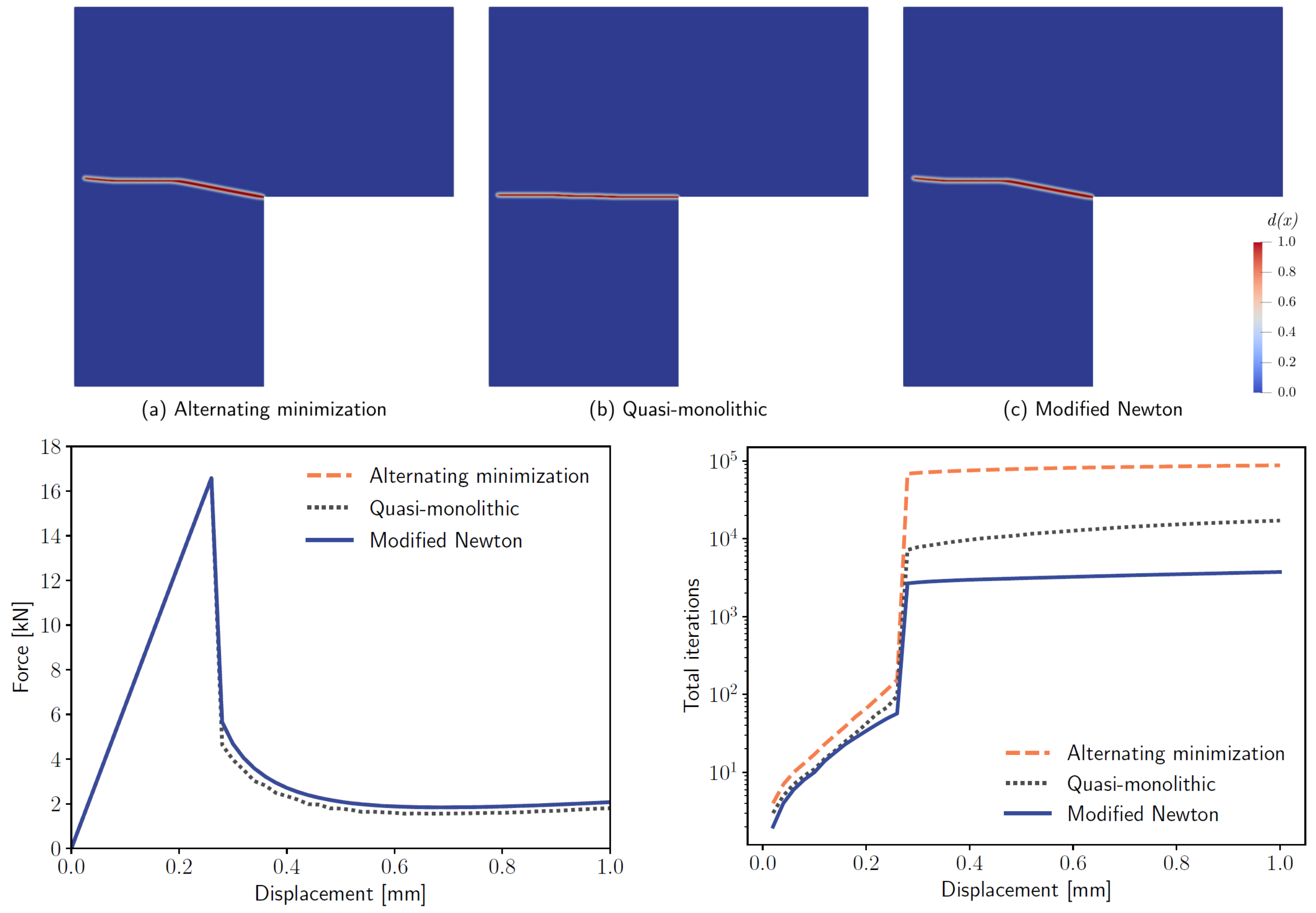

Figure 6: Comparison of the predicted cracks, force-displacement responses and number of iterations of the three solvers. The proposed modified Newton solver yielded an acceleration of the computation time by a factor of 12. [2]

Conclusions

- The complete tensile and fracture behavior of unidirectional FFF PLA , along with its fracture process, was characterized.
- The computational cost associated to PFM was reduced by a factor of 12 using a modified Newton solver.

References

[1] K. R. Hart and E. D. Wetzel, Engineering Fracture Mechanics, 2017.
[2] O. Lampron, D. Therriault, M. Lévesque, Comput Methods Appl Mech Eng, 2021.

ACKNOWLEDGMENTS

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