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On the application of power ultrasonics for accelerated fatigue testing and defect engineering

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DAMAGE MECHANISMS IN CFRP AND THE NEED FOR ULTRASONIC FATIGUE TESTING

Fatigue in Carbon Fiber Reinforced Polymers (CFRP) is a damage accumulation process where multiple micro-cracks from the fiber-matrix interface (due to local inhomogeneity) or from the matrix (due to defects) interact with each other to cause delamination (see *Figure 1*).

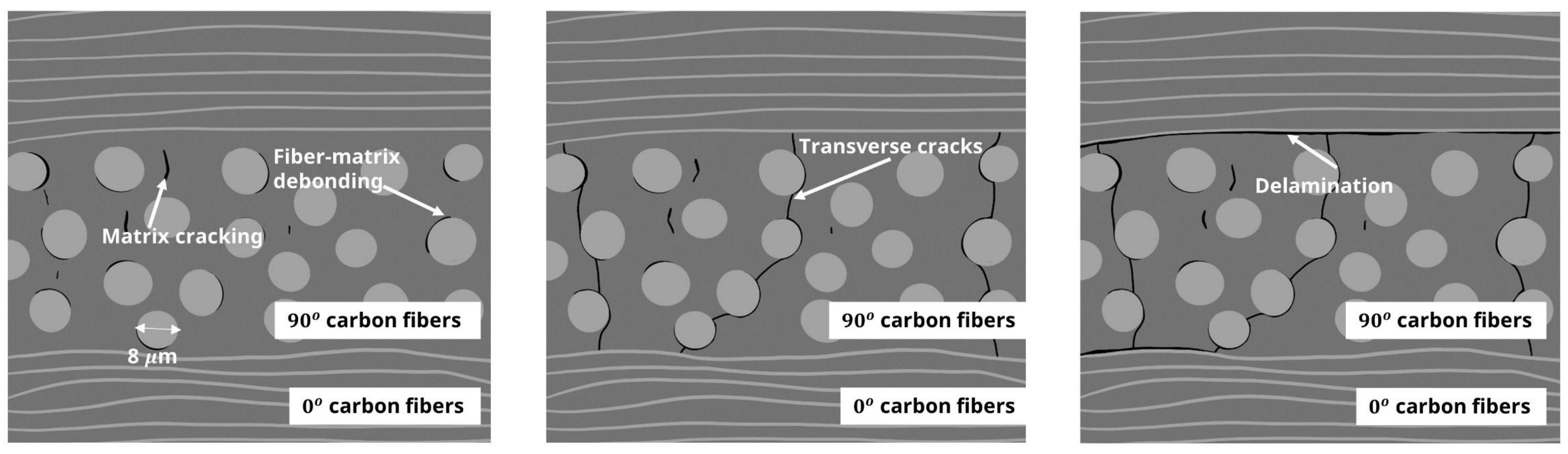

Figure 1: Schematic representation of delamination resulting from the fiber-matrix debonding, matrix cracking and transversal ply cracking in CFRP.

Literature so far on CFRP laminates has shown that crack initiation occurs within the first few hundred cycles [1]. The transition from transverse ply crack to delamination depends however on the applied fatigue stress. If a cyclic stress is applied whose amplitude is close to the threshold of damage growth, delamination can :

- occur from weak links such as defects in matrix or fiber-matrix interface
- stop or the delamination growth rate can slow down.

The Ultrasonic fatigue testing method provides a time and cost efficient solution in comparison to the conventional fatigue tests (test frequency: 1-100 Hz), in particular for the characterization of initiation and evolution of such delamination mechanisms which can occur over a period of several million fatigue cycles.

CYCLIC THREE-POINT-BENDING

In contrast to servo-hydraulic systems, the cyclic load is applied at a fatigue frequency of 20 kHz. This is possible if the test specimen is designed such that its natural frequency for first transverse bending mode matches with that of the resonance unit (see *Figure 2*) of the ultrasonic fatigue testing system, which is also 20 kHz.

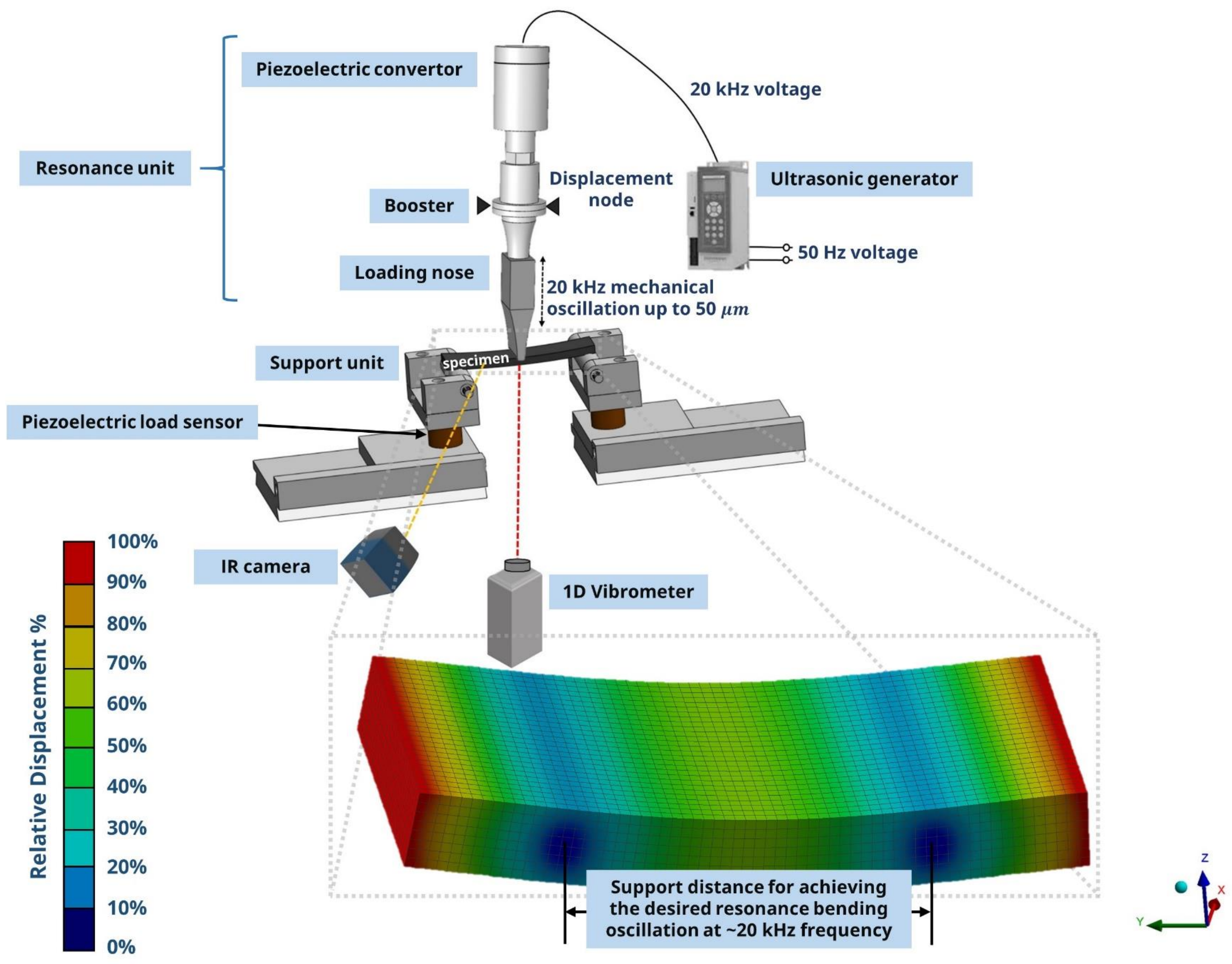

Figure 2: Schematic of the test setup for three-point-bending load and ANSYS workbench simulation to achieve resonance oscillation of first transverse bending at 20 kHz.

A maximum oscillation displacement of 50 μm can be achieved at the bottom end of loading nose. To guarantee a permanent contact between the loading nose and the specimen during resonance, a monotonic deflection greater than 50 μm is necessary. The cyclic displacement is then superimposed on the monotonic deflection.

SPECIMEN DESIGN FOR ULTRASONIC FATIGUE

The ultrasonic fatigue experiments will be realized on carbon fiber 5-H satin fabric reinforced polyetherketoneketone (CF-PEKK) material system with the orthotropic layup. PEKK is a semi-crystalline thermoplastic polymer whose glass transition temperature (162^o C) and processing temperature (375^o C) makes it suitable for primary structures in aerospace applications.

If the specimen is considered to be a beam, the natural frequency for the first bending eigenmode is given by [2]:

$$f_{1B} = \frac{(k_1 L)^2}{2\pi} \cdot \frac{d}{L^2} \sqrt{\frac{E_L}{12\rho}}$$

Modal analysis is carried out with nine elastic constants and density ($E_{11}, E_{22}, E_{33}, G_{12}, G_{13}, G_{23}, \vartheta_{12}, \vartheta_{13}, \vartheta_{23}$ and ρ) as material parameters in ANSYS Workbench for the CF-PEKK material system to determine the specimen geometry and the distance between the support units (see *Figure 2*).

ANALYSIS OF DEFECTS

During the fatigue experiments, the applied load, specimen deflection, resonance frequency and surface temperature (see *Figure 3*) are continuously monitored (see *Figure 2*). At intermediate stages, the experiments are paused for stiffness measurement (using static three-point-bending setup) and to quantify damage evolution. The surface damage visualization will be carried using Scanning Electron Microscope (SEM) while the volumetric damage will be investigated using X-ray mirco-tomography (in cooperation with Fraunhofer IAF and FMF).

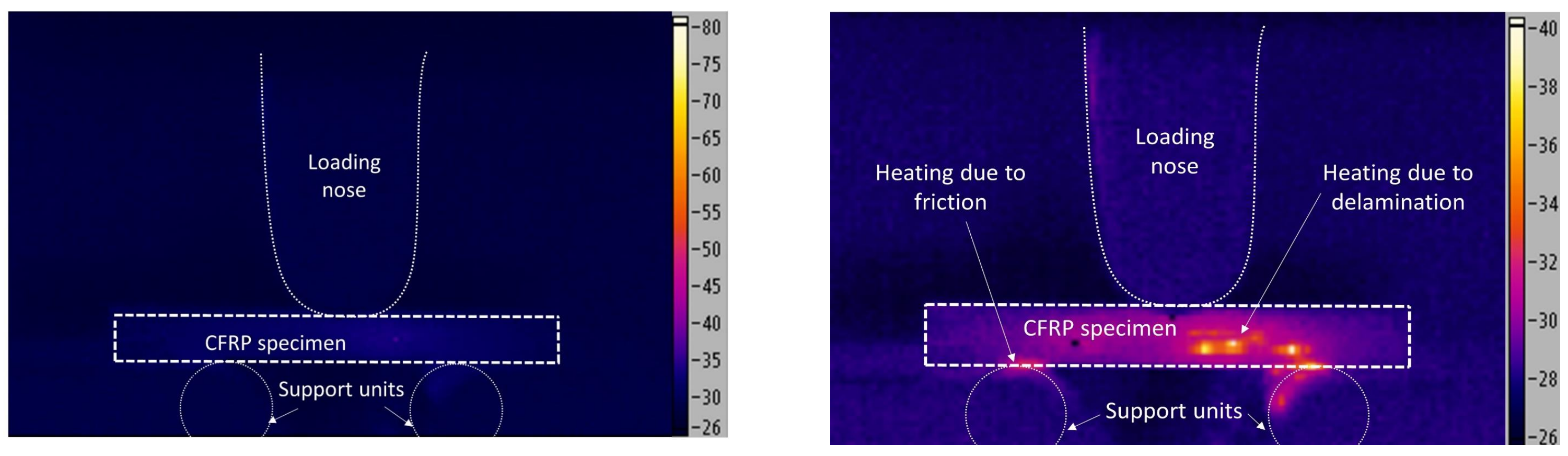

Figure 3: Thermograms (from [3]) depicting rise in temperature due to delamination.

For the three-point-bending loading under the first transverse bending mode, maximum shear stresses are found in the area between the support units and the loading unit (see *Figures 3* and *4*). When the shear stresses exceed the local strength in these regions, damage initiates from defects and material inhomogeneity. If such defects can be detected and localized, the future steps would be to use techniques such as ultrasonic consolidation in order to heal the matrix cracks and fiber-matrix debonding through application of pressure and local heating.

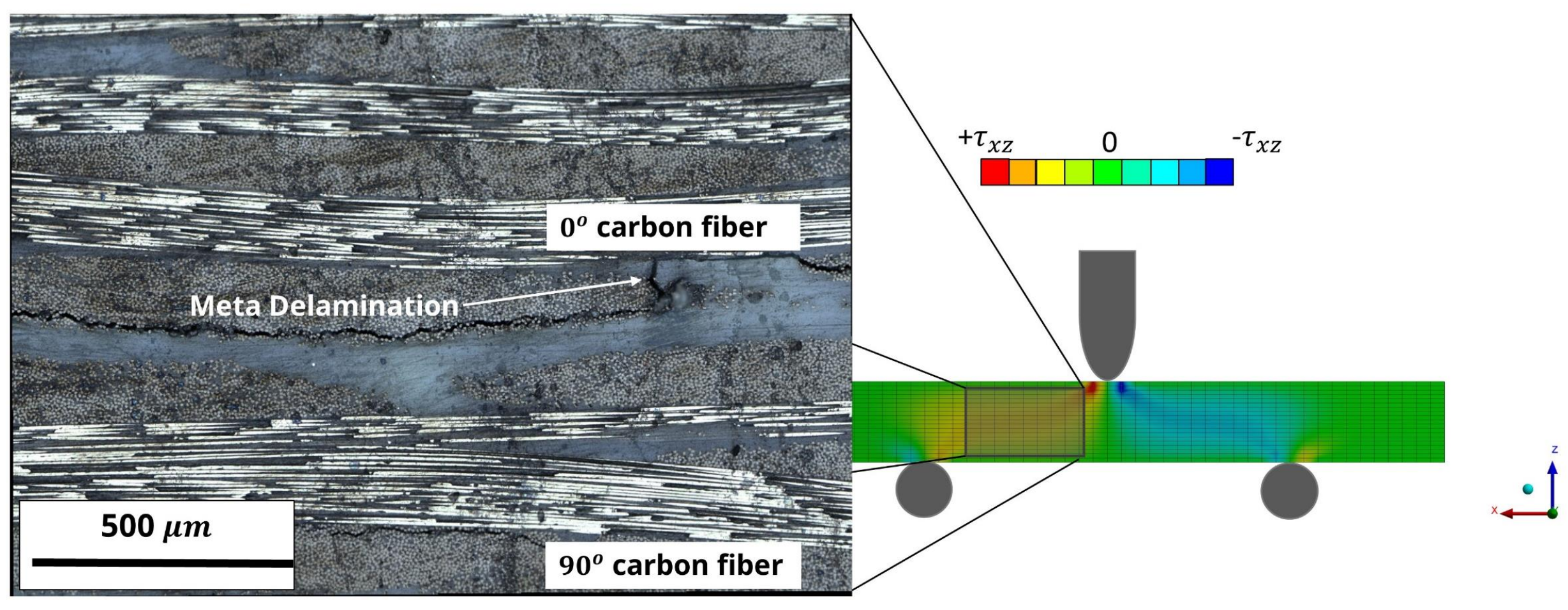

Figure 4: ANSYS Workbench simulation for visualization of the highly stressed regions and the fracture surface of a damaged specimen showing meta-delamination.

REFERENCE

[1] R.P. Harrison and M.G. Bader, Damage development in CFRP laminates under monotonic and cyclic loading, *Fibre Science and Technology* **18**, pp. 163 – 180 (1983).

[2] S.S. Rao, Vibration of continuous systems, 6 ed. Hoboken, USA: John Wiley and Sons Ltd.; 2019

[3] D. Backe, F. Balle, D. Eifler, Fatigue testing of CFRP in the very high cycle Fatigue (VHCF) regime at ultrasonic frequencies, *Composites Science and Technology* **106**, pp. 93 – 99 (2015)