Additional data for the *In-situ full field measurement during inter-facial debonding in single fiber composite under transverse load* publication

Ilyass Tabiai[a], Rolland Delorme[a], Daniel Therriault[a], Martin Levsque[a]

[a]*Laboratory of Multis-scale Mechanics, cole Polytechnique Montral, 2900 boul. douard-Montpetit, Montral, QC, Canada*

Abstract

The following document is an extension of the *In-situ full field measurement during inter-facial debonding in single fiber composite under transverse load* publication. It contains guidelines for the experimental results for the single fiber experiment of epoxy matrix and PTFE fiber, epoxy matrix and galvanized steel matrix, modified epoxy matrix and PTFE fiber and modified epoxy matrix and galvanized steel matrix. The detailed data from the experiments is provided with this document as *CSV* files.

Keywords: Stereoscopic digital image correlation, Interface fracture, Single fiber composite, Debonding, Fiber reinforced composites

DOI :

1. Materials and Geometry

1.1. Materials

Commercially available galvanized steel fibers having a diameter of 0.9mm were purchased from *Duramax* and Polytetrafluoroethylene (PTFE) monofibers having a diameter of 0.99 mm were acquired from *Zeus Inc.* Two different polymer resins were used as matrices: *(1)* 10 parts in mass of Epon™ 862 epoxy resin with 4 parts of Epikure™ 3274 as a curing agent and *(2)* the previous mixture with an additional 3.5 parts of elastomer modified epoxy, to improve its ductility (acquired from *Momentive Performance Materials Inc*).

Table 1 lists the mechanical properties for the constituents used as fibers and matrix in these experiments.

1.2. Specimen geometry

The composite samples tested in this work contained a single fiber embedded inside a standard *ASTM D638 Type I* dogbone sample. Figure 1-a schematically shows the manufactured composite samples. Figure 1-b schematically shows molds used to produce *ASTM*

D638 Type I dogbone samples featuring a single metal or PTFE fiber oriented perpendicularly to the tensile loading direction. The molds were 3D-printed using a Fused Deposition Modeling (FDM) printer. Once prepared, the resin/curing agent mixtures were degassed, poured into the mold, degassed again and left to cure for 24 hours at room temperature.

2. Test procedure

The complete test procedure is thoroughly detailed in [Paper]. The procedure will be summarized here.

Table 1: Elastic and thermal material properties of the studied constituents. The galvanized steel wire and PTFE's properties were obtained from the manufacturer's data sheet. The properties for epoxy and modified epoxy were obtained by testing the materials. The epoxy and modified epoxy's CTE was measured using a thermomechanical analysis machine (TMA).

Material	Young Modulus (GPa)	Poisson's ratio	CTE($/^{o}$C)
Epoxy	2.5 ± 0.90	0.46	60.6×10^{-6}
Modified epoxy	2.8 ± 0.32	0.44	67.6×10^{-6}
Galvanized steel wire	200	0.29	12×10^{-6}
PTFE wire [**?**]	$0.39 - 0.60$	0.36	$126 - 180 \times 10^{-6}$

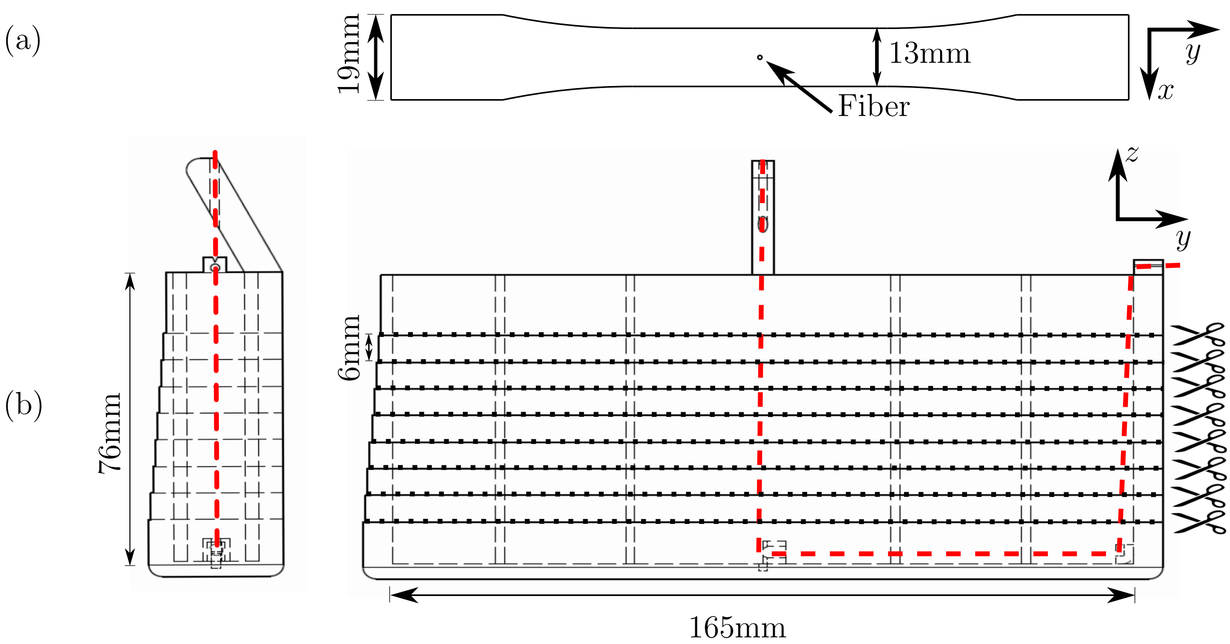

Figure 1: **(a)** *ASTM D638* specimen with an embedded fiber along the z direction.
(b) Computer Aided Design (CAD) design of the 3D printed mold. The dotted path in red shows how the fiber was held to the mold. The mold was cut using an abrasive-waterjet-cutting machine to provide individual *ASTM D638 Type I* specimens with a single fiber perpendicular to the tensile direction once the epoxy was cured.

2.1. *Tensile test*

The force measured by the load cell and the tensile machine's cross-head displacement were acquired at a frequency of 2Hz. A picture was acquired by both cameras at each acquisition. The computer on which the cameras were connected to was also equipped with a *National Instruments* data acquisition device to acquire the cross head displacement and force from the load cell at the exact moment each picture was acquired. The region covered by the cameras was of approximately $\approx 7\text{mm} \times 6\text{mm}$, with a resolution of $\approx 2.5 {}^{\mu\text{m}}/_{\text{px}}$.

2.2. *Digital Image Correlation software parameters*

The subset sizes selected for each specimen are provided in Table 2, as well as the main DIC parameters (subset, step and correlation type) used for each test.

The subset size in DIC is defined as the set of pixels contained in a square centered on the pixel currently being tracked. The subset for each tracked pixel are used as a filter in the deformed image to find the same pixel again. The pixels contained in this square are

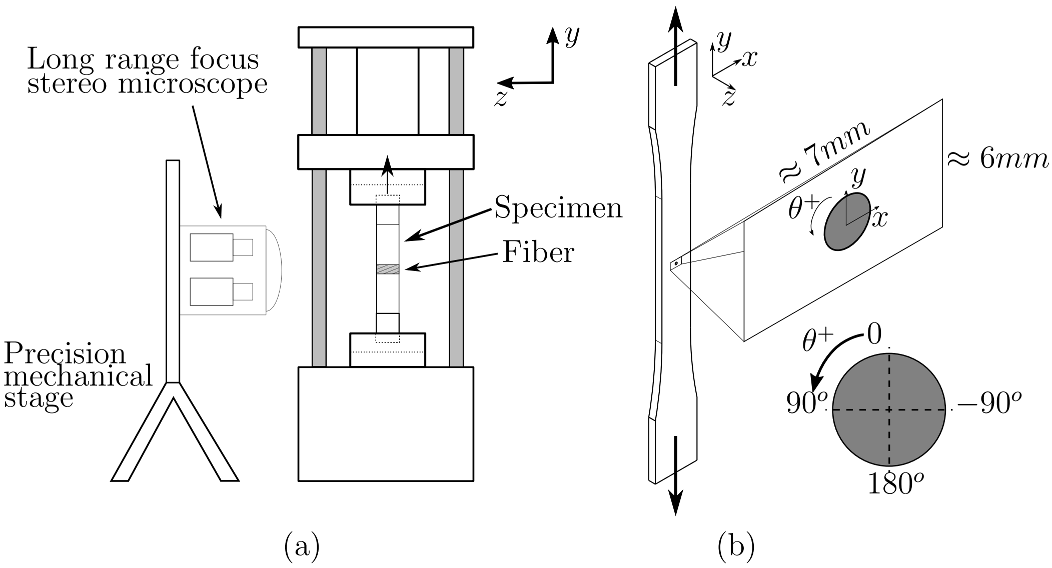

Figure 2: **(a)** Schematic representation of the 3-axis high precision linear stage supporting two cameras with a long range focus stereo microscope used to track the fiber during the test. The optical setup was installed in front of the electromechanical testing machine. **(b)** Isometric view of the specimen. The arrows show the tensile direction. The fiber is visible as a circle in the middle of the specimen. The cameras observe the specimen in the xy plane.

Matrix	Fiber	Subset	Step	Correlation type
Epoxy	PTFE	81	2	Direct
Modified epoxy	PTFE	81	2	Direct
Epoxy	Galvanized steel	85	2	Direct
Modified Epoxy	Galvanized steel	55	2	Direct

Table 2: Subset, step and type of correlation (direct or incremental) parameters selected for each analysis.

called the subset of a pixel. The subset size is conditioned by the paint dots size since it should contain numerous dots to yield accurate DIC results.

The step size is defined as the spacing of the points that are analyzed during correlation. The displacement of the pixels in between is obtained through interpolation.

3. Data structure

3.1. Data package content

- **Fiber-Matrix.mp4 :** This file provides a video of the experiment with the DIC results (strain along the y direction) overlaid as a contour plot on the raw images.

- **Fiber-Matrix.csv :** This file provides the datset detailed in section 3.2.

- **Images :** This folder contains the raw images used for the DIC analysis.

- **CSV :** This folder contains the complete CSV results for each image. Each image is presented as a CSV file with all values measured using DIC (such as displacements) or computed by the DIC software (such as strains). The description of each column contained in each CSV file is provided in section 3.3. More details are available in the VIC manual [1].

3.2. Test data: tensile test machine

Results presented here were extracted from stereo-images taken during each experiment. In each test, the specimen is pulled under transverse load while the stereo-microscope setup snaps pictures at regular intervals. At the same moment each picture is taken, the tensile test machine cross-head and load-cell data are also recorded.

The data obtained from the tensile test machine is recorded in a *.csv*[2] file, which is available in the data package folder. Each file is named using the following denomination `Fiber-Matrix.csv`. Each file has the following values in each column:

- **Index:** Number (index) of the stereo-image taken.

- **Time (s):** Time t since the beginning of the test. Instant at which the stereo-image was taken.

- **Displacement (mm):** Displacement applied on the specimen at instant t as measured by the electromechanical testing machine.

- **Force (N):** Force applied on the specimen at instant t as measured by the electromechanical testing machine.

[1]http://www.correlatedsolutions.com/support/index.php?/Knowledgebase/Article/View/12/1/output-variables-in-vic-2d-and-vic-3d

[2]https://en.wikipedia.org/wiki/Comma-separated_values

- **Stress (MPa):** The fiber is neglected when computing the stress in the gage length. This value does not represent the stress in the fiber's vicinity, but the stress in the gage length for a specimen with similar geometry without a fiber.
  $\text{Stress} = \frac{\text{Force}}{\text{Gage length thickness} \times \text{Gage length width}}$
- **Strain (%):** The global strain is computed using the following formula:
  $\text{Global Strain } \% = \frac{\text{Displacement}}{\text{Initial grip-to-grip length}} \times 100$

3.3. Grid data: Digital Image Correlation

The images are analyzed using the *VIC3D* commercial software. After analysis, grid data is extracted from the software. The grid data presents displacement and deformation values for each pixel analyzed. The folder of each specimen contains *.csv* files from different moments of the experiment. For example, the file called `PTFE-Epoxy-0990.csv` contains the results from the PTFE Epoxy specimen at index *0990*. By looking at the line for which `Index` is `0990` in the file `PTFE-Epoxy.csv` it is possible to find out the *Displacement, Force, Stress and Strain* corresponding to the `PTFE-Epoxy-0990.csv` file.

Each Digital Image Correlation file contains the following variables:

- **X, Y, Z** [mm]: Initial position along the X, Y and Z axis. The X axis is the horizontal one, Y axis is vertical and the W axis is the out-of-plane axis.
- **U, V, W** [mm]: Displacement along the X, Y and Z axis from the reference image. These values are 0 for the initial image.
- **exx, eyy, exy** [1]: Strain in the X, Y and shear strain.
- **e1, e2** [1]: Major and minor principal strain.
- **gamma** [1]: Principle strain angle, measured counterclockwise from the positive X axis.
- **sigma** [pixel]: The 1-standard deviation confidence in the match, in pixels. A value of 0 indicates a perfect match, higher values indicate noise or possibly a failed match. If this value is higher than 0.050, the pixel is not tracked anymore.