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Deep Learning Segmentation of X-Ray Computed Tomography of Woven Composites

Collin Foster

Sandia National Laboratories

Overview

Non-destructive morphological evaluation of a scaled woven thermal protection system (WTPS) is a reliable tool to build predictive response models for multi-physics simulations. The micro- and meso-scale geometry is first captured with X-ray computed tomography, then the relevant regions of interest must be segmented from the raw data. Thermal performance is highly connected to weave orientation and accurate capture of the directionality of the fiber-woven tows is critical to correct material property imposition for simulation. This study explores deep convolutional neural networks (DCNN) to extract warp- and weft-oriented tows and compares their respective performance in the texture-based segmentation task. The results of the segmentation methods are then evaluated for geometric and transport effective properties compared to a reference segmentation. We showed that U-Net, MCDN (V-Net), and MS-D Network can produce highly accurate segmentations of the warp, weft, and matrix phases of both a loose and compact weave. Probability maps from the MCDN showed that effective properties will vary at most 10% due to segmentation uncertainty. The analysis concluded that poor accuracy to diffusive effective properties is linked to a segmentation method's ability to accurately capture the weave volume fraction of the material phase.

Introduction

This study puts emphasis on woven thermal protection systems that are highly compact, have an intertwined tow-architecture, and overlap between ply layers. Scanner improvements have led to accessible high-fidelity data acquisition at university-level facilities and the ability to digest and discriminate relevant features within large image files (>10 GB) is a critically important and evolving area of research. Composites pose a unique challenge, as it is often difficult to distinguish between key phases and isolate tow direction without arduous manual semantic segmentation through possibly thousands of slices [1-2]. Of particular interest to simulating WTPS is capturing the mesoscale, or tow-scale, as its geometry strongly influences the effective material properties [3]. This begins with isolating the warp and weft fabric tows, then assigning relevant constitutive properties approximating the microstructure. While there is visibly no difference in intensity between the tows' directionality (Fig. 1a), machine learning relies on artificial neural networks to discriminate on the mesoscale between the warp and weft tows using shape and texture information. Two material architectures with distinct fiber volume fractions are selected, in order to assess method performance on structures of largely different compactness. This is an analysis of imperfect as-manufactured weaves that gives greater insight into DCNN performance unbiased by having a pristine weave.

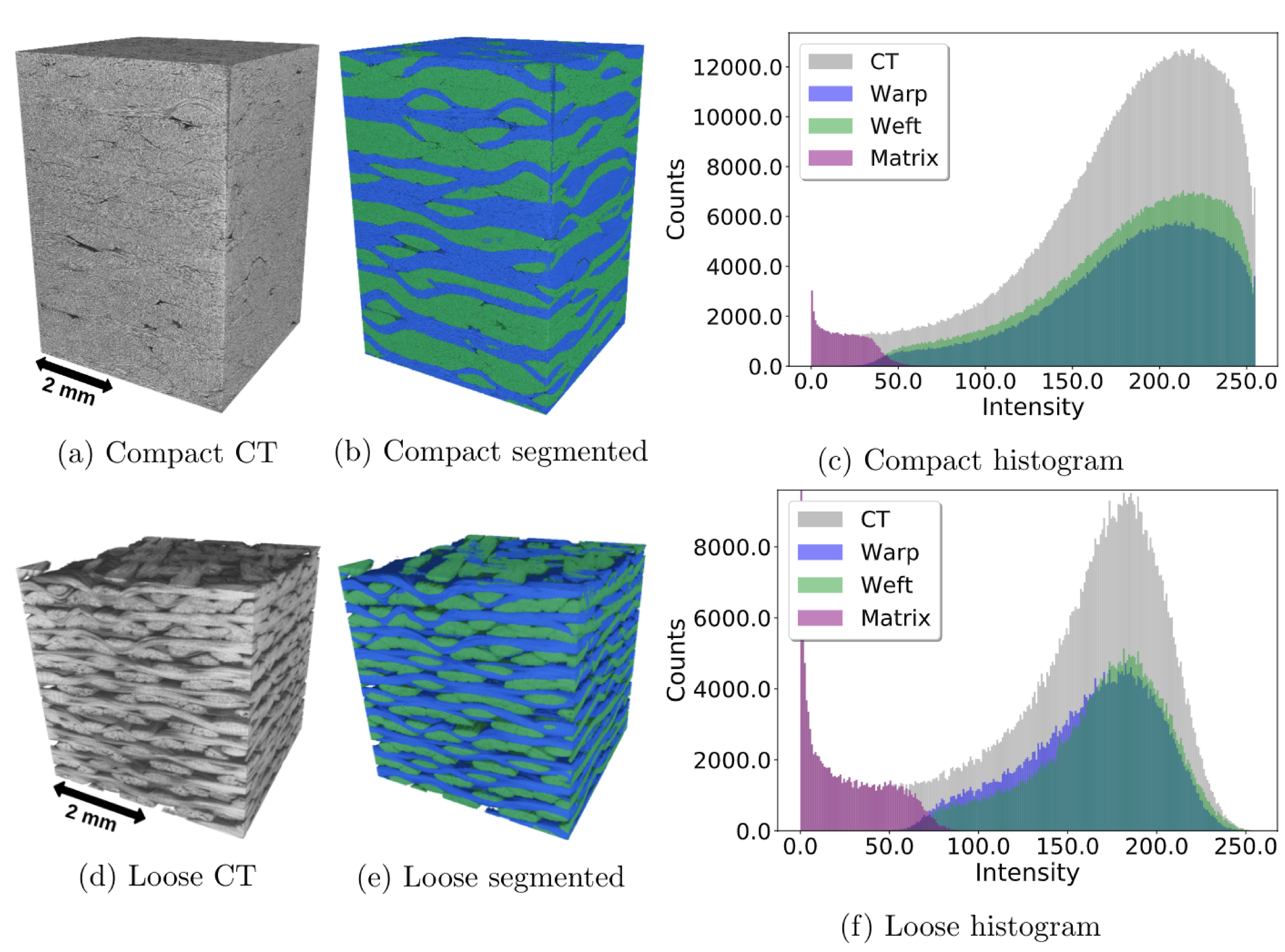


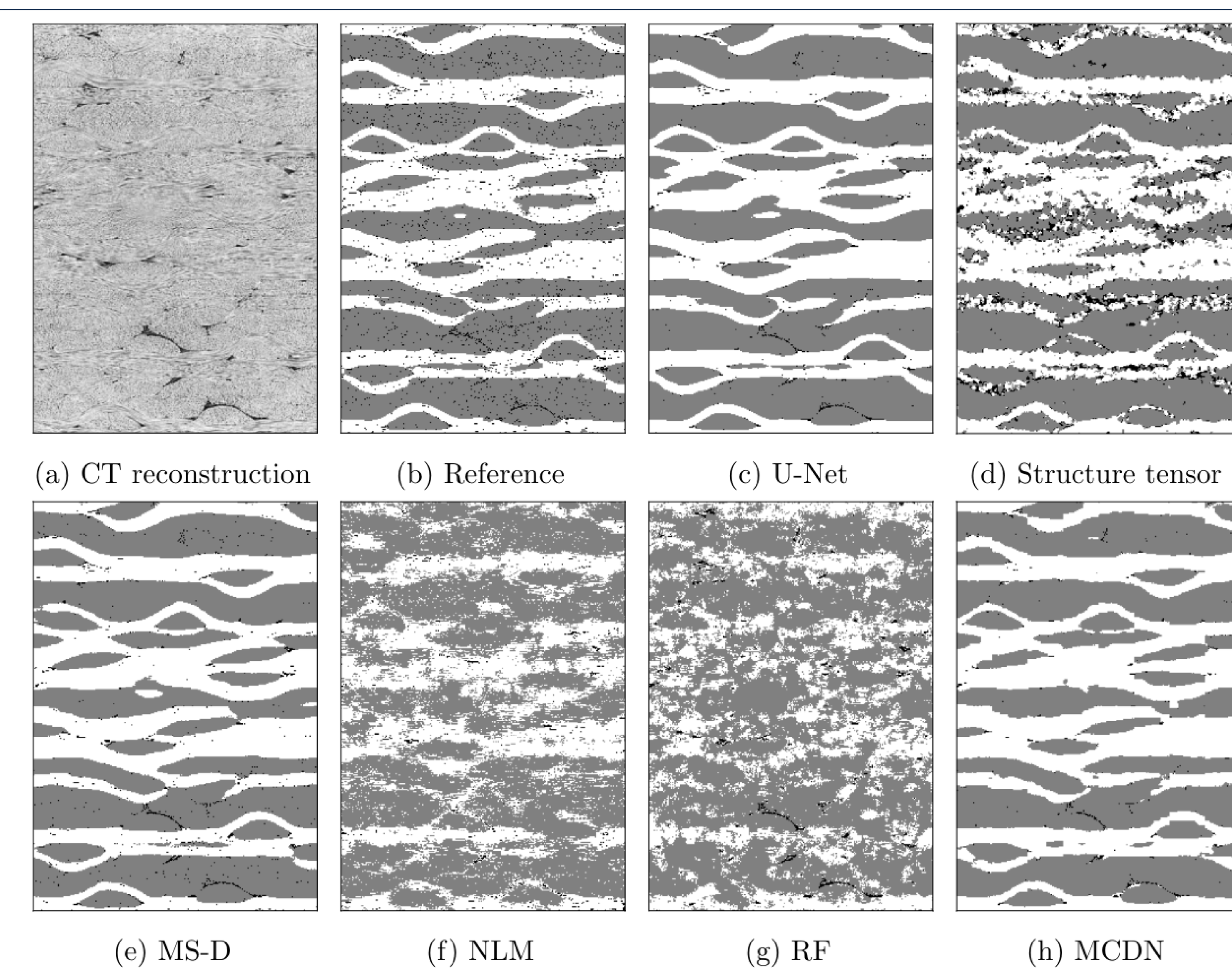
Figure 1. Geometry and phases of the compact and loose coupons. (a) - (c) represent the compact coupon, (d) - (f) are the loose. Each segmentation is 3-phases representing warp-, weft-tows, and matrix.

Method and Setup

Through either learned or predisposed filters, ML strategies semantically segment low-intensity contrast images based on per-voxel intensity, texture, and contribution to larger shapes. Explored and compared is a sampling of vetted, contemporary, and developing machine learning algorithms tasked with segmenting the warp, weft, and matrix phases of the WTPS coupons. Each method uses unique training parameters for inference, discussed in the results along with metrics to evaluate their performance. The segmentation methods evaluated are: U-Net implemented in Dragonfly, structure tensor (ST), Monte Carlo Dropout Network (MCDN), mixed-scale dense network (MS-D), non-local means (NLM), and Random Forest (RF). All machine learning methods are trained with the same pre-labeled reference segmentation, and infer upon a previously unseen volume to evaluate their error. With the complete compact volume segmented, finite element simulations are performed with multi-physics code Sierra/Aria [4] to connect choice of method with resulting effective properties. Effective thermal conductivity (TC) and tortuosity (Tort) are calculated in the in-plane and (IP) out-of-plane (OOP) directions by solving the diffusion residual of the governing energy equation [3].

Results

The resulting segmentations are shown for the compact weave in Fig. 2 and error tabulated in the associated table. The U-Net implemented in Dragonfly is very accurate on the compact weave. Small errors in labeling can be seen in Fig. 2c, occurring largely at warp and weft intersections, where a tow will move in the OOP direction, reducing the accuracy of the CNN filters as it is trained primarily on the opposing directionality of the warp and weft tows. The result of the structure tensor calculation is viewed in Fig. 2d, and while providing lower accuracy compared to its ML counterparts, the ST performed satisfactorily with ample texture-based information. From the RF segmentation, the compact weave ultimately gave the worst results in the study as indicated by Fig. 2g. In the compact weave, the highly-accurate MS-D does a notably better job retaining more matrix-phase information than U-Net and MCDN, shown in Fig. 2e, capturing more of the small pixels. The NLM segmentation is shown in Fig. 2f, where one can generally see the main features of the warp and weft tows, noted by that the algorithm can break down in the warp-weft interface, as a sharp change in texture information. Overall, the MCDN achieved high scores for both the loose and compact weave compared to its U-Net counterpart, making better use of that volumetric training data.



	Weave	U-Net	ST	MS-D	NLM	RF	MCDN
Pixel (%)	Compact	91.7	81.8	93.3	77.8	67.5	91.6
Rand (%)		87.2	75.5	89.9	72.3	57.4	87.2
Jaccard (%)		84.7	71.7	87.6	67.8	50.6	84.5

Figure 2. Accuracy of segmentation techniques applied to compact TPS.

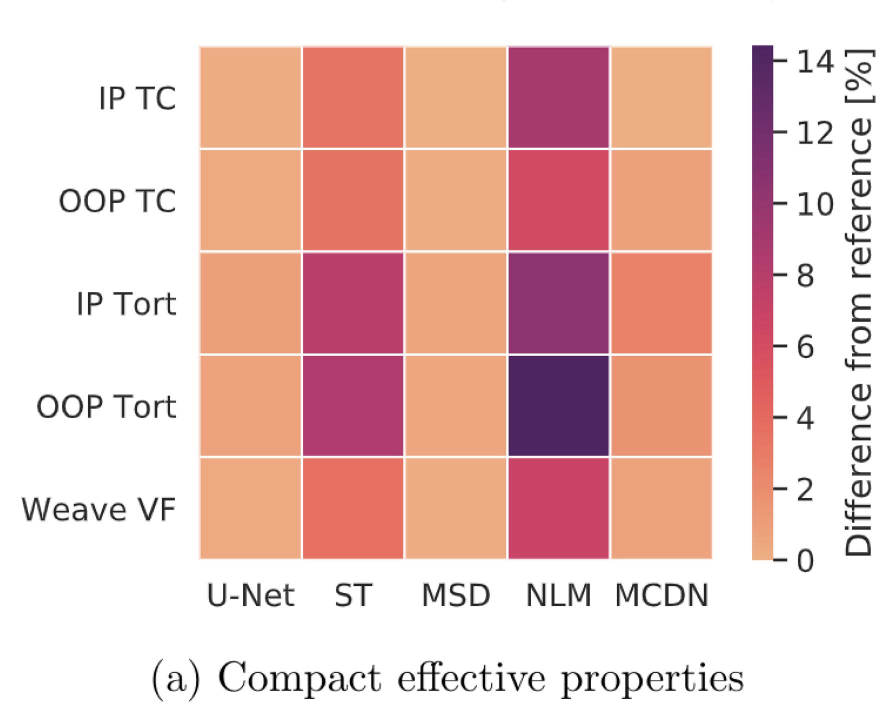


Figure 3. Results of effective property calculations represented as percent difference from reference segmentation.

The heat map shown in Fig. 3 shows the effective properties of each method taken as a percent difference from the reference segmentation. A total variation of at most 15% in the compact weave is observed, suggesting overall that all segmentation methods provide satisfactory predictions of effective properties. Generally shown in Fig. 3 the OOP properties exhibited higher deviation from the reference compared to IP due the fact that in both the multi-layer coupons the largest source of error was at layer-interfaces, shifting OOP diffusion estimations. Highly accurate methods such as U-Net, MS-D, and MCDN show less than 5% difference in effective properties when compared to the reference, and near zero difference in weave volume fraction. Deviations in weave volume fraction will impact the effective properties by obstructing thermal pathways and hindering particle diffusion through the matrix phase.

Conclusions

Although the reference segmentation is still prone to researcher's subjectivity in labeling, the U-Net, MCDN, and MS-D, proved highly-accurate in segmenting warp / weft / and matrix classes in the compact WTPS. Non-NN approaches such as ST benefit largely from minimal parameter tuning, and the Fast RF allows for high levels of control and customization of a robust NN architecture, though lack of accuracy is shown in this study. Depending on a researcher's available computation resources, labeled training data, and tolerance for parameter tuning, each segmentation method has its own benefits for low contrast weave segmentation. For the U-Net, MS-D and MCDN, any differences in weave volume fraction is largely due to the misclassification of micro-voids, resulting in small variations in weave volume in the volumetric mesh. ST and NLM both carried the highest deviations in effective properties which is clearly identifiable with large differences in weave volume fraction.

Contact

Collin Foster, PhD Candidate
Center for Hypersonics and Entry Systems Studies
Department of Aerospace Engineering
University of Illinois at Urbana-Champaign
Email: collinf3@illinois.edu
Website: chess.grainger.illinois.edu

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