BRIDGING THE GAP BETWEEN MODELING AND ANALYSIS FOR 3D WOVEN COMPOSITES USING DIGITAL VOLUME CORRELATION

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Abstract
The inherent weaving pattern of 3D woven composites is employed for the dialog between different descriptors. The continuity of information is achieved with Digital Volume Correlation and the key concept of conservation of the topology. A complete test scenario is devised in which different manufactured woven samples are compared to the theoretical textile arrangement. The results confirm the effectiveness of the method.

1. Introduction

The ever-increasing interest in composite materials has generated a high demand for tailored modeling tools, proper characterization methods and accurate simulations. Unfortunately, since these are usually developed and carried out independently from each other, there are limited means for them to benefit from (and be confronted to) each other. However, 3D woven composites do present an interesting characteristic that allows to overcome such challenges. This material is defined by the yarns (reinforcement phase) being woven after a three-dimensional weaving pattern and held together by a resin (matrix phase). As such, all of the aforementioned analyses deal directly or indirectly with an intrinsic topological characteristic of the material: the weaving pattern. Additionally, it should be noted that the geometrical disposition of yarns is of great importance for the performance of composite materials. In like manner, it is highly desirable to be able to interpret the various results obtained from these different analyses from a unique standpoint: that of their underlying topology.

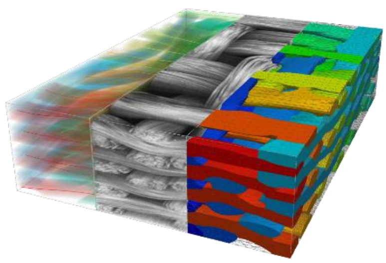


Figure 1. Different descriptors for a given 3D woven composite: CAD model (arrangement of yarns), high resolution CT image and FE mesh (yarns and resin).

Finally, this research suggests Digital Volume Correlation [1] for the comparative analysis between different representations (or descriptors) of woven composites so as to guarantee the digital continuity of information. This is obtained by retrieving the displacement field relating the studied configurations. These configurations can depict different manufactured samples observed through computed tomography (CT), different simulation results expressed under the finite element (FE) framework, or even the textile definition being shown as a 3D model (e.g. CAD). Examples of such descriptors for a single 3D woven composite are illustrated in Figure 1.

2. Methods

2.1. Correlation procedure

Digital Volume Correlation (DVC) is a widely used technique used for registering volume pairs. For a reference image $f(\boldsymbol{x})$ and a test image $g(\boldsymbol{x})$, DVC minimizes the L_2 norm of residuals

$$\eta = f(\boldsymbol{x}) - g\big(\boldsymbol{x} + \boldsymbol{u}(\boldsymbol{x})\big) \cdot v_1(\boldsymbol{x}) - v_0(\boldsymbol{x}) \tag{1}$$

with the optimal displacement field $\boldsymbol{u}(\boldsymbol{x})$ and intensity level corrections $v_0(\boldsymbol{x})$ and $v_1(\boldsymbol{x})$. The *continuous* transformation defined by $\boldsymbol{u}(\boldsymbol{x})$ implicitly includes an assumption of invariant topology between the analyzed volumes (i.e. the yarns are assumed to be organized in the same fashion). Whereas, the corrections $v_0(\boldsymbol{x})$ and $v_1(\boldsymbol{x})$ explain all extrinsic phenomena to such a hypothesis.

2.2. Regularization techniques

In order to deal with the ill-possedness of the problem, three regularization techniques are used together.

First, the correction fields $\boldsymbol{u}(\boldsymbol{x})$, $v_0(\boldsymbol{x})$ and $v_1(\boldsymbol{x})$ are restricted to a space of lower dimensionality using a global variational formulation [2]. These can be expressed as a function of their degrees of freedom $\{\boldsymbol{a}\}$ and a set of chosen kinematic basis $\phi_i(\boldsymbol{x})$ (from the FE framework, for example)

$$\boldsymbol{u}(\boldsymbol{x}) \approx \sum a_i \, \phi_i(\boldsymbol{x}) \tag{2}$$

Second, the fields are penalized by their "distance" to a sought property. The displacement field is penalized by the L_2 norm of its *equilibrium gap* [3]. This measures how far the current estimated displacement field is from being the solution of a homogeneous elastic problem. Similarly, the intensity level correction fields are penalized by the L_2 norm of their Laplacian. This strategy can be seen as a set of filters that locally dampen steep gradients so as to ensure smooth and differentiable fields.

Finally, a multiresolution strategy is used so as to progressively evolve from a global and coarse vision of the entire textile towards a finer one that deals with the yarns. This approach reinforces the preservation of topology, thus making the algorithm robust and numerically efficient.

2.3. Correlation for virtual models

Given that DVC is implemented so as to deal with volumes (3D images) of the same nature, all descriptors not expressed originally with *voxels* (e.g. a FE mesh) need to be converted into an intermediate representation: that of the image.

This preprocessing step consists in projecting them into a regularly structured space. In other words, to discretize them so as to obtain an image composed of *voxels*. These can be made meaningful by carefully choosing the values that are given to these newly formed *voxels*. A natural choice would be to assign labels according to the structure they originally belonged to. This would result in volumes with as many intensity levels as there are phases in the material. Since the present analysis considers only two phases: the yarns and the resin (or air), the obtained images are binary.

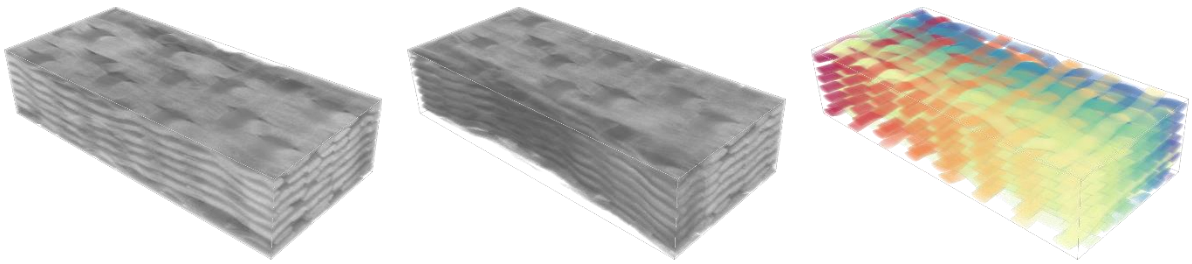
However, the accuracy obtained from DVC is directly related to the abundance of gradients found in rich textures. As such, these binary images, in which the yarns as “solid” structures with well-defined boundaries, pose a challenge to DVC. Here, the gradients are located only at the boundaries. Hence, widening these boundaries would increase the effective correlation length. This can be achieved with a Gaussian blur in which the kernel radii are set according to the largest displacement sought.

Finally, this “translation” of descriptors is completely lossless. That is, for a given voxel it is always possible to retrieve the corresponding information in the original representation, and vice versa.

3. Results

The available descriptors are a pair of CT images and a virtual model. All of these entities coincide on the same weaving pattern. They are illustrated in Figure 2.

For testing purposes, one sample was intentionally altered during the manufacturing process: two yarns were removed. This sample is chosen as the reference configuration. Then the remaining two descriptors are to be used as the test (deformed) configurations for two separate analyses. The final result will exploit the previously obtained results.



(a) (b) (c)

Figure 2. The results are given for the (a) reference and (b) test samples observed through CT, as well as for the (c) virtual model with the same textile definition.

3.1. Correlation between samples

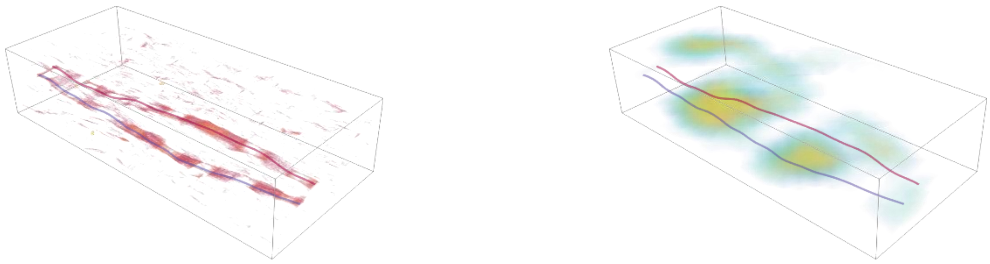
The found correction fields identify the yarn displacements and changes in intensity levels required to transform the test sample towards the reference sample. In sight of the known existing weaving anomaly (missing yarns), it is interesting to perform two types of inquiries.

First, the different phenomena that violate the assumption of constant topology are captured with the semi-residual due to displacement only:

$$\eta_u = f(\boldsymbol{x}) - g\big(\boldsymbol{x} + \boldsymbol{u}(\boldsymbol{x})\big) \tag{3}$$

These are shown in Figure 3a, where the missing yarns are prominently highlighted.

Second, the displacement field $\boldsymbol{u}(\boldsymbol{x})$ itself can be manipulated so as to obtain the *relative* strains between the studied samples. As Figure 3b shows, considerable deformations occur around the missing yarns. This is in agreement to the expected (and observed) accommodations of neighboring yarns.



(a) (b)

Figure 3. A good alignment is observed for the (a) semi-residual due to displacement only and (b) trace of the *relative* strain tensor with the intentionally missing yarns (shown as neutral fibers).

3.2. Correlation between a sample and the virtual model

First, the preprocessing step of discretization and blurring must be applied on the virtual model. The newly obtained image, shown in Figure 4a, is registered with the reference sample (CT).

Then, the found displacement field $\boldsymbol{u}(\boldsymbol{x})$ can be applied to the original virtual model so as to obtain a new model that is aligned to this manufactured sample. This result, shown in Figure 4b, leads to the segmentation and identification of yarns.

It should be noted that the algorithm is capable of dealing with the entire textile and aligns all yarns with their corresponding positions observed on the CT volume. Even the virtual yarns without observed counterparts are just moved along with their neighbors.

(a) (b)

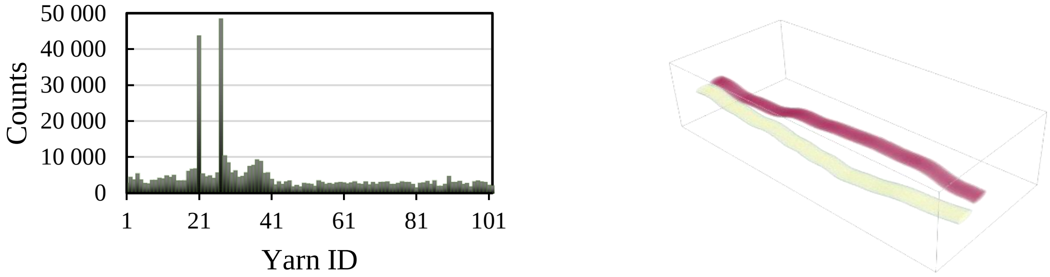
Figure 4. This procedure requires the (a) discretized representation of the virtual model and allows to compute the (b) aligned virtual model for the reference sample.

3.3. Combined results

Finally, the results of the two preceding calculations can be combined. In particular the semi-residual due to displacement only obtained in Section 3.1 and the aligned virtual model obtained in Section 3.2. The former map the "amount" of topological differences of each voxel in the reference configuration. Similarly, the latter designates the yarn to which every voxel belongs to (in the same configuration).

Now, it is possible to count the presence of these anomalies per yarn, as shown in Figure 5a. From this tally, two yarns clearly distinguish themselves from the rest. A new virtual model which only considers these yarns is shown in Figure 5b. These yarns correspond to the missing yarns.

This final result amounts to an automatic nondestructive testing (NDT) procedure for 3D woven composites. The robustness of this approach relies on the fact that it uses a reference configuration. This provides the algorithm with a vast amount of information with a considerably low effort from the user. Moreover, the missing yarns were not sought, but rather appeared as anomalies that did not conform to the reference or to the assumption of constant topology.



(a) (b)

Figure 5. (a) The amount of topological differences per yarn helps identify (b) the missing yarns.

4. Conclusions

The dialog between different descriptors of woven composites was established with Digital Volume Correlation. This technique is based on the key concept of conservation of the topology. It quantifies the deformations required to relate different configurations. Additionally, it is capable of dealing with weaving anomalies, such as loops and missing yarns. These measurements can then be used to extract indicators, either of quantitative (relative strains) or qualitative (images of residuals) natures. Finally, the technique allows the use of a single topological description from the design of the composite up to its manufacturing.

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