MICRO-SCALE ARTIFICIAL WEAVE GENERATION CAPABILITIES FOR THERMAL PROTECTION SYSTEM MATERIAL MODELING

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Introduction

Thermal Protection System (TPS) modeling requires accurate representation and prediction of the thermomechanical behavior of ablative materials. State-of-the-art TPS materials such as Phenolic Impregnated Carbon Ablator (PICA) have a proven flight record and demonstrate exceptional capabilities for handling extreme aerothermal heating conditions. The constant push for lightweight materials that are flexible in their design and performance, and hence allow for a wide range of mission profiles, has led NASA over the past years to develop its Heatshield for Extreme Entry Environment Technology (HEEET). HEEET is based primarily on a dual layer woven carbon fiber architecture and the technology has successfully been tested in arc-jet facilities [1]. These recent developments have sparked interest in the accurate micro-scale modeling of composite weave architectures, to predict the structural response of macro-scale heatshields upon atmospheric entry. This effort can be extended to incorporate in-depth failure mechanics analyses as a result of local thermal gradients or high-velocity particle impact.

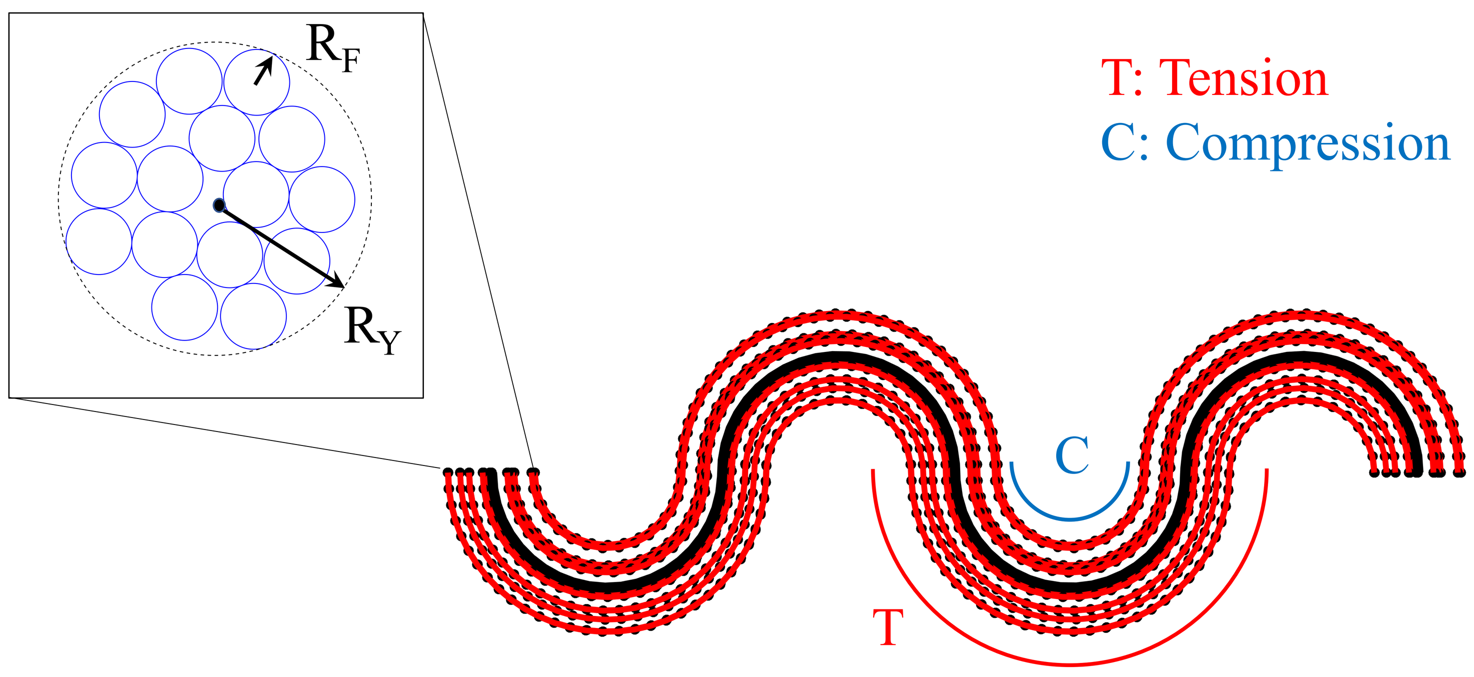

Fig. 1 BU initialization of a semi-circle wave yarn in the weft direction, the centroidal axis of which is shown in black. Fibers that make up the yarn are shown in red.

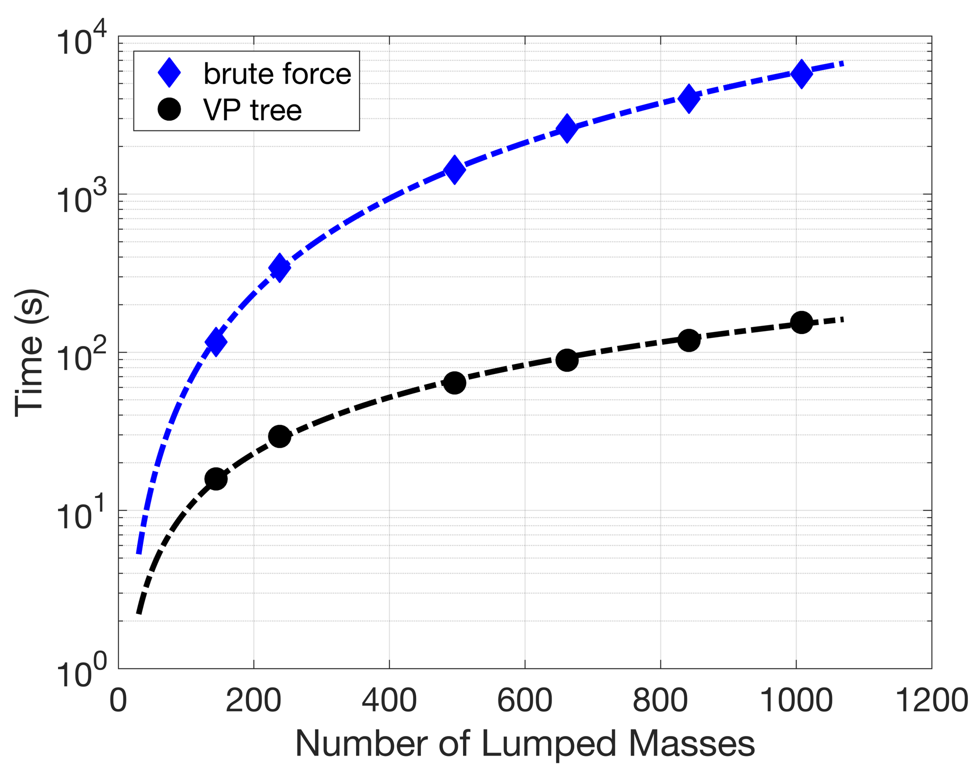

Fig. 3 Improvement in simulation time for a 4-by-4 weave using a VP tree for contact searching as opposed to the brute force method. The number of nodes is increased by adding up to 3 fibers per yarn.

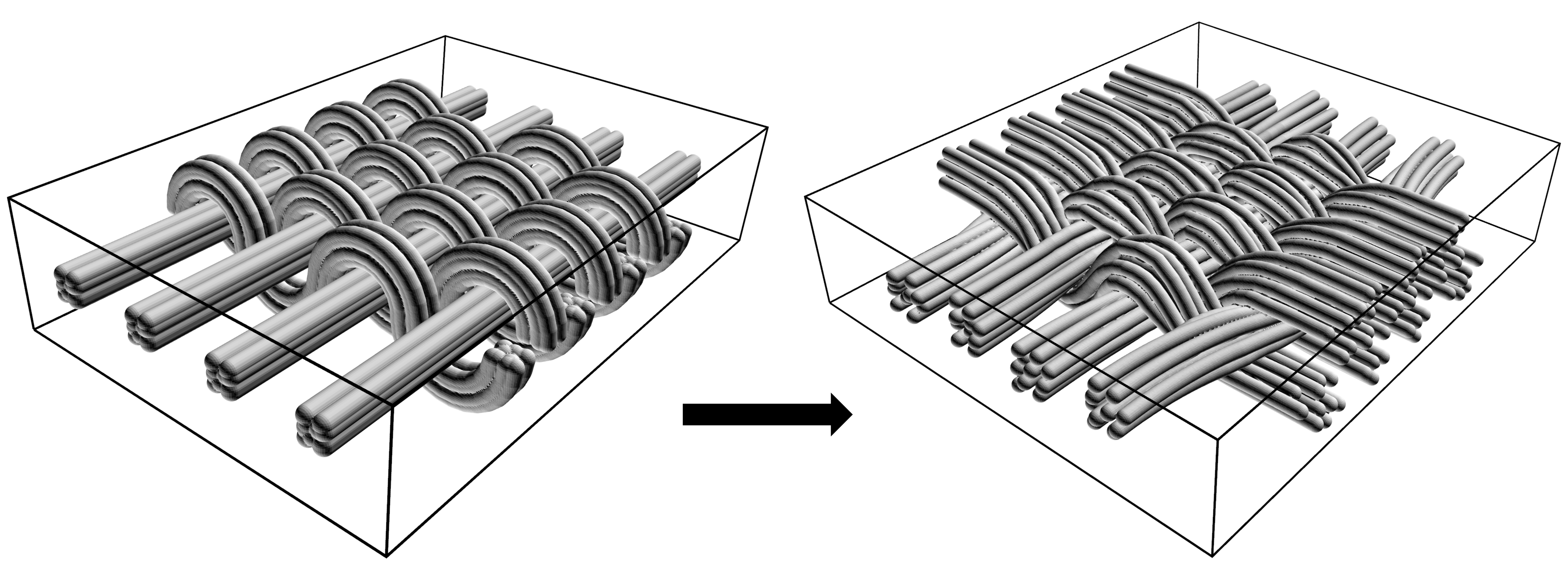

Fig. 4 Initial and final states of a stretching simulation using the BU approach for a 4-by-7 weave with 10 fibers per yarn. Visualized in PuMA.

Top-Down Approach

The Top-Down (TD) approach replaces the initialization from the BU approach with another automized routine which couples to the third-party TexGen [7] library for modeling textile structures. An in-house weave diagram is used to specify a complex 3D weave architecture using a given number of yarns, each with their own respective circular or ellipsoid cross-sectional area, as shown in Fig. 5. TexGen models the individual yarns as single solid elements. Instead of solving for the minimum bounding circle, or ellipsoid, the encompassing circle is provided and populated with as many fibers as physically possible as shown in Fig. 6. This is done by reversing the bounding algorithm from Fig. 1. Yarns in the weft direction are layered across the yarns in the warp direction using a numbering scheme. The nodes describing each 3D yarn centerline are redistributed following the same interpolation scheme as described in the BU approach to alleviate the pre-tensioned state. Future work consists of maturing the stretching procedure in 2D and 3D as well as optimizing for computational efficiency, after which the focus will shift to the calculation of the effective 3D anisotropic thermomechanical properties using PuMA.

PuMA: https://software.nasa.gov/software/ARC-17920-1

Weaving Methodology

This work presents the preliminary stages of an artificial weave generation design tool. The objective is to develop a robust tool for extracting the effective three-dimensional anisotropic material properties of unit cells. High-fidelity representation of the micro-scale structure, simple and automated initialization and fast computation of the stretched shape and material properties are key. Two different approaches, Bottom-Up and Top-Down, are used in initializing weave architectures in both 2D and 3D. Fibers are modeled as 1D beams discretized using a lumped mass model. Current capabilities allow stretching of 2D unit cells through the application of tension-, contact- and damping forces at each node *p* of beam element *m* as described by Eq. (1) – (3) [2]. External forces are applied at the outer ends of each fiber along the fiber axis.

- Tension: $$\vec{F}_T\big|_p^m = \frac{E_L A}{l_0}\left(\left|\vec{r}_{p+1}^{\,m} - \vec{r}_p^{\,m}\right| - l_0\right)\frac{\vec{r}_{p+1}^{\,m} - \vec{r}_p^{\,m}}{\left|\vec{r}_{p+1}^{\,m} - \vec{r}_p^{\,m}\right|} \quad (1)$$
- Contact: $$\vec{F}_C\big|_p^m = \left(\frac{2\sqrt{2}E_T l_0 d^2}{3 l_c}\left(\frac{h}{d}\right)^{3/2}\frac{\vec{r}_p^{\,m} - \vec{r}_q^{\,n}}{l_c}\right)\Bigg|_{h>0} \quad (2.1)$$
$$l_c = \left|\vec{r}_p^{\,m} - \vec{r}_q^{\,n}\right| \quad (2.2)$$
$$h = d - l_c \quad (2.3)$$
- Damping: $$\vec{F}_D\big|_p^m = -2\vec{v}_p^{\,m}\sqrt{\frac{E_L A}{l_0}M_p^m} \quad (3)$$

Bottom-Up Approach

The Bottom-Up (BU) approach initializes 2D weaves based on a mathematical formulation for the position of all lumped masses. This method allows for specification of the number of fibers within a yarn, among other parameters, as shown in Fig 1.

Rather than employing routines to compute the most densely packed configuration of congruent fibers within a yarn [3], the requirement is relaxed to provide a mere tight packing. This approach is taken with an eye to real-life manufacturing processes, as shown in Fig. 2 in the case of HEEET, whereby optimal packing is not realistic. Instead, a user-defined number of fibers are clustered around the origin in a Gaussian manner and repelled away from each other using a flocking algorithm. A minimum bounding circle algorithm [5] provides the yarn radius R_Y as a function of the number of fibers and fiber radius R_F. The yarn centerline is computed and the 2D fiber distribution profile from Fig. 1 mapped onto it at fixed angular intervals. Thickness in the radial direction inevitably results in regions of compression and tension. To offset this effect and remove the pre-tensioned state upon initialization, an interpolation scheme is used to redistribute the masses at equidistant intervals along the originally defined spline.

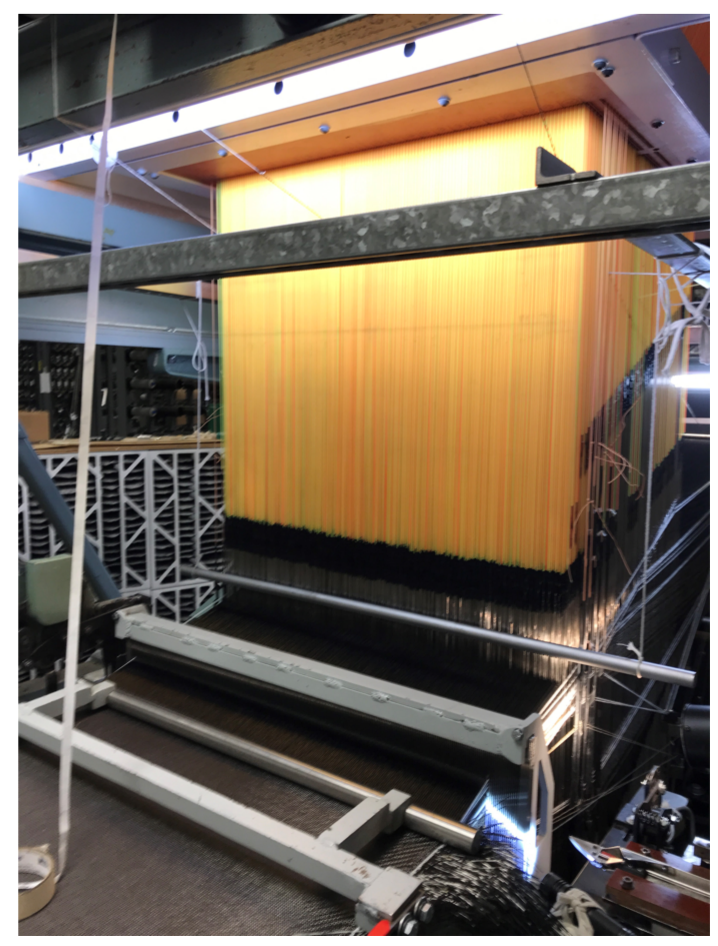

Fig. 2 Loom used in the 3D weaving process for dual layer HEEET [4].

Contact searching within a weave is performed using a vantage-point (VP) tree to reduce the number of Hertzian-based contact [2] operations within a timestep from N^2 to $O(N\log(N))$, where N represents the total number of lumped masses in the architecture. With contact searching being the bottleneck in accelerating simulation time, the VP tree has vastly improved performance as shown in Fig. 3. Realizing that self-contact is not possible in the shown weave architectures, this provides room for further improvement. The weaves are stretched into shape using the forces from Eq. (1) – (3) until a converged state is reached as shown in Fig. 4. The convergence criterion is met when the magnitude of the resulting total force on each node *p* falls below a user-defined tolerance.

Current capabilities are being implemented in the Porous Microstructure Analysis (PuMA) [6] tool which has been used the visualize the initial and final states in Fig. 4.

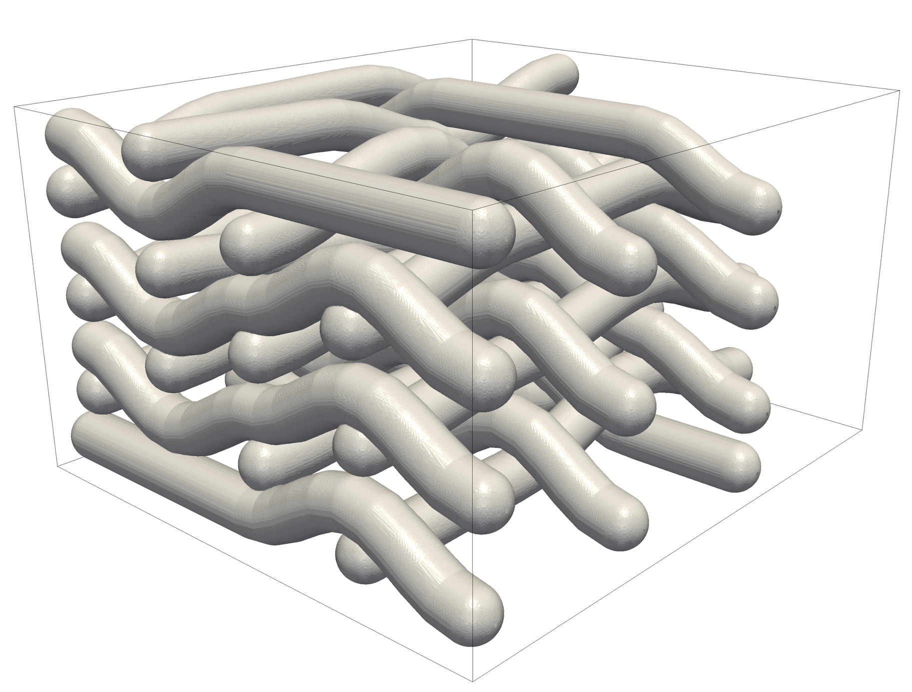

Fig. 5 Initialization of a 3D weave with 23 yarns via TexGen using the TD approach. Each yarn has a circular cross-section. Visualized in ParaView.

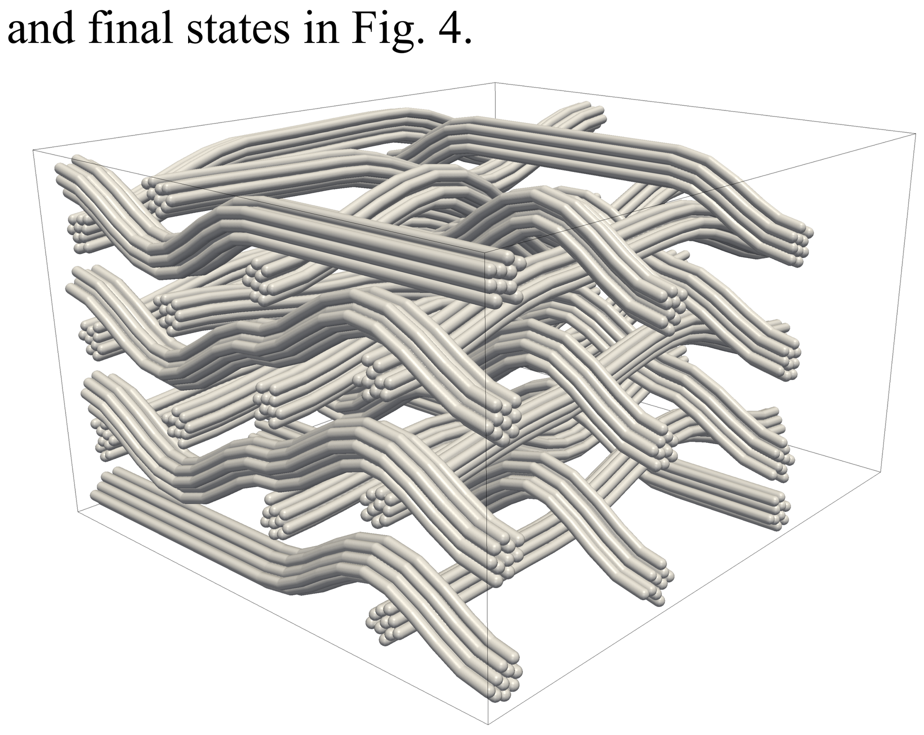

Fig. 6 Transformation of a 3D weave by filling up the yarn cross-sections with as many fibers as possible, in this case 10. Visualized in ParaView.

References

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