

Arc-jet Testing of Continuously Woven Aeroshells—Spiderweave—for Adaptable Deployable Entry Placement Technology

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The Adaptable, Deployable Entry Placement Technology (ADEPT) is an entry system that, when deployed, creates a large, umbrella-like drag surface that can be used to decelerate spacecraft during atmospheric entry, resulting in lower entry loads and heating than a rigid aeroshell of equivalent mass. Until needed for entry, the system can remain stowed, enabling missions to overcome launch vehicle fairing diameter constraints. 12-inch diameter umbrella-like articles, similar to a small reentry probe using ADEPT, were tested in the Ames 20-MW Aerodynamic Heating Facility. Performance of the test articles built with a novel, continuously woven aeroshell construction (called Spiderweave) is compared against those built with legacy construction styles. In addition, candidate thermal protective layer treatments applied to structurally sensitive regions of the aeroshell are assessed using data from on-board instrumentation as well as facility optical instruments.

I. Introduction

THE Adaptable, Deployable Entry and Placement Technology (ADEPT) is a mechanically deployable hypersonic decelerator offering unique advantages and benefits over existing rigid heatshield entry systems. ADEPT employs an umbrella-like deployable structure with a “skin” that is a 3-D woven carbon fabric to serve as a thermal protection system (TPS) and as a structural surface that transfers aerodynamic deceleration forces to the underlying ribs [1, 2]. The ADEPT structure is folded during launch and then deployed prior to atmospheric entry, enabling the entire flight system to be packaged into a smaller volume than a rigid aeroshell. The ADEPT Project has previously tested fabric in the arc-jet facility with success in demonstrating integrity of the fabric under tensile load while being heated to flight-relevant temperatures [3, 4]. Subsequent testing in the arc-jets has occurred using the Small Probe Re-Entry Investigation for TPS Engineering-Cloth (SPRITE-C) configuration, demonstrating the success of system-level performance [5]. In 2018, the ADEPT project demonstrated the system concept of deployment and entry during a sub-scale sounding rocket flight test, called ADEPT SR-1 [6].

The SPRITE-C geometry shown in Fig. 1 consists of a rigid spherical nose cap (forward portion) and an octagonal pyramid aft/flank portion made of 3-D woven carbon fabric that is supported by rigid ribs. (The deployable aft/flank fabric region is often referred to as the carbon fabric skirt (CFS).) The fabric panels that stretch between the ribs are called “gores” or “acreage” portion of the fabric. Figure 1 shows where the fabric surface makes contact with the underlying structure, transferring both aerodynamic and thermal loads from the un-supported acreage fabric to the ribs. It is crucial, then, that this interface be protected and optimized to ensure mission success.

Aerothermal tests of the novel Spiderweave seamless ADEPT carbon fabric aeroshell and a control mode of legacy construction were conducted in the 20-MW Aerodynamic Heating Facility (AHF) 18-inch nozzle using a SPRITE-C geometry with a diameter of approximately 12 inches. Legacy aeroshell constructions known as “Stitched Joint” join individual gores of fabric together with high-density stitching that binds separate pieces together with an underlying splice panel (tie strip,) making the stitched seam a crucial interface for the aeroshell to maintain integrity during the entry pulse. The Spiderweave fabrication approach, developed in partnership between NASA Ames Research Center (ARC) and Bally Ribbon Mills (BRM), resulted in an aeroshell structure with similar weave architecture, fabric construction, and fiber orientation compared to legacy formats, but without stitched joints. The weaving process devised by BRM for Spiderweave creates a folded tubular product that when unfolded and trimmed results in an octagonal pyramid net shape with continuous circumferential tows. End-view cross-section diagrams of Spiderweave and Stitched Joint construction

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are shown in Fig. 2. Although the Spiderweave does not require a tie-layer, it is included in the test article fabrication with non-structural stitching to be equivalent in thermal mass to the Stitched Joint construction so that comparisons may be made.

To protect the sensitive interface, a protective layer (P/L) treatment is applied over the rib region, covering the joint, and secured with non-structural stitching. Several candidate protective layer (P/L) designs were considered, shown in Fig. 3, and applied to both the Spiderweave and Stitched Joint rib region. Team design discussions resulted in the selection of two primary P/L designs which were designated Type-A and Type-B. Type-A consists of a doubled-over wrap of 2-layer blended carbon-phenolic fabric with a thin strip of elevated-temperature cure, B-stage film adhered on top. The Type-B P/L consists of 2-layer carbon fabric wrapped around a thin strip of film with another thin strip of film adhered on top. The consistency of the film prevents the material from wicking into the surrounding acreage material, while forming and adhering to the P/L fabric when cured under vacuum. The film and the phenolic in the the Type-A blended P/L fabric is intended to ablate and thus provide some protection for the P/L retention stitches as well as the joint below. Secondary P/L candidates that were included in the test were constructed from plain-weave fabric that is not folded. Type-X1 is a 4-layer blended carbon-phenolic that is stitched to the fabric joint with no film covering, leaving the stitching exposed, and Type-X2 is identical to Type-X1 but covers the stitching with film.

II. Preliminary Results

A total of eight test articles were fabricated for the Spiderweave test series – four Spiderweave (SW) articles, and four Stitched Joint (ST) articles. Pre-test CFD simulations shown in Fig. 4 were utilized to predict surface environments such as heat flux, pressure, and shear stress which informed facility settings used during the arc-jet campaign. The arc-jet test campaign, referred to as AHF347, took place in July of 2021 with six of the eight test articles. The two remaining articles were reserved for comparison with post-test articles. Each test article was exposed to the same nominal condition for approximately the same duration, shown in Table 1. Calorimeter data obtained in the test was in-line with expectations. A detailed comparison of the CFD simulations and measured environments will be provided in the final manuscript.

Thermocouples installed on the rib structure and acreage fabric, as well as optical instrumentation from the facility, were used to obtain temperature measurements at locations of interest, such as the region over the P/L. As shown in Fig. 5, rib structure temperatures beneath Treatment A reached similar levels across each article construction style while rib temperatures under Treatment B were distinctly different between Spiderweave and Stitched Joint articles. One possible explanation for this difference is that the high-density, structural stitching used to join individual panels of fabric effectively increases thermal conductivity in the Stitched Joint articles as a result of thread spanning the layers of fabric, and the Type B design may not continuously provide cooling through pyrolysis gas blowing as there are only two thin film layers in the treatment. Conversely, thermocouples attached to the rib under Treatment X1 measured similar or lower temperatures than Treatment X2, despite not having a film protective treatment. Further work to address the differences in performance will be defined in the final manuscript.

Surface temperature time histories for each P/L location on each Spiderweave and Stitched Joint article are shown in 6. For each test article, the surface temperature exhibits distinct periods of variation in the early portion of the model exposure. One possible explanation for difference is that the protective film applied over the fabric undergoes dramatic changes as it ablates in the arc jet. However, based on pyrometer measurements shown in Fig. 6, the change in temperature is inconsistent and it is not clear whether the temperature at the surface is reduced or increased as a result of the film application ablation process. Additional samples in AHF347 were tested using simple film applications as P/L treatments and comparisons will be made to detail the film performance in the final manuscript.

From previous test experience, exposure duration for each model was determined to allow for small amounts of carbon fabric material recession, also referred to as "layer-loss", across the test article. This was done to generate realistic performance stress during reentry where layer-loss would be present, but not so much that the aeroshell fabric would recess completely, destroying the test article. The shape of the article in both its pre-test and post-test state are captured using a high-precision laser scanner. Comparison between the pre-test and post-test shape of each model reveals the combined layer-loss and deformation. Preliminary results for two such articles are shown in Fig. 7. Model deformation is recorded along the rib length where rib designation is denoted using the protective thermal treatment applied, "A" for example, followed by the number of the rib "2". The "-" and "+" denote whether the specific rib call-out is either negative (-) or positive (+) distance from the test article center. From approximately -3 inches to +3 inches, the spherical nose cap difference is off-scale as it recessed greater than 0.05 inches. Both the Spiderweave and Stitched Joint article exhibit similar levels of deformation, with most regions deforming between -0.01 inches and -0.03 inches.

Still, the Stitched Joint article possesses characteristically different deformation patterns than the Spiderweave article that holds true for each other article tested. Detailed differences in fabric recession for Spiderweave and Stitched Joint articles will be reported in the proposed paper.

Table 1 AHF347 run matrix of model insertion order, exposure, 4-inch iso-q calorimeter measurements, and insertion facility settings in the AHF 18-inch nozzle. The model distance from the nozzle exit-plane was approximately 12 inches.

Run	Model	Insertion	Exposure [s]	Heat Flux [W/cm ²]	Pressure [kPa]	Test Box Pressure [Torr]	Arc Current [A]	Main Air Flow Rate [g/s]	Arc Heater Pressure [kPa]
2	Calorimeter	1	2	229	8.5	-	2000	330	839
2	SW-2	2	30	-	-	2.1	2000	330	839
2	ST-2	3	30	-	-	2.1	2000	330	839
2	Calorimeter	4	2	207	8.4	-	2000	330	839
3	Calorimeter	1	2	228	8.5	-	2000	330	839
3	SW-3	2	30	-	-	2.0	2000	330	839
3	ST-3	3	30	-	-	2.1	2000	330	839
3	Calorimeter	4	2	212	8.5	-	2000	330	839
4	Calorimeter	1	2	226	8.4	-	2000	330	838
4	SW-4	2	30	-	-	2.0	2000	330	838
4	ST-4	3	30	-	-	2.1	2000	330	838
4	Calorimeter	4	2	208	8.4	-	2000	330	838

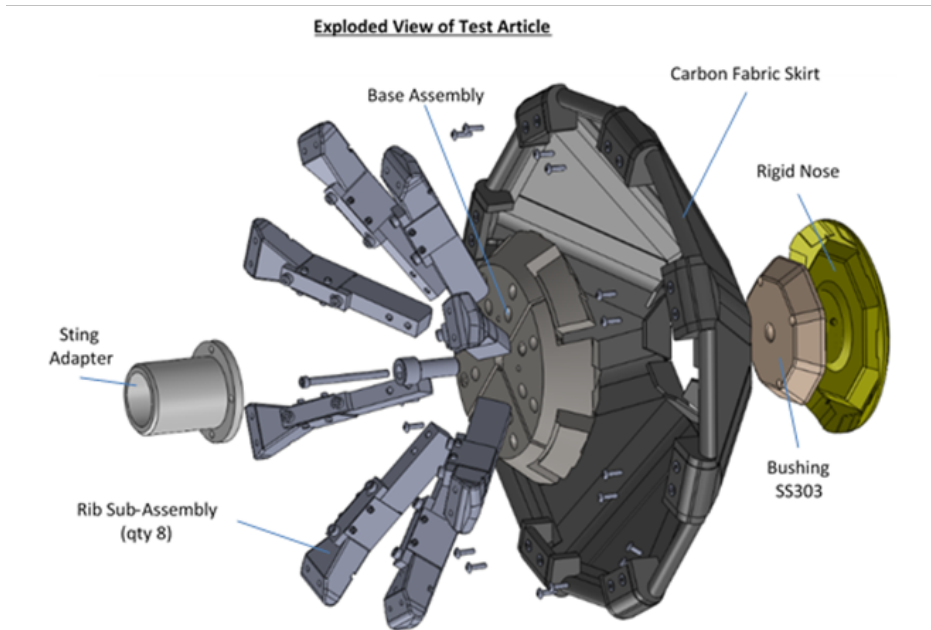


Fig. 1 SPRITE-C test article exploded view.

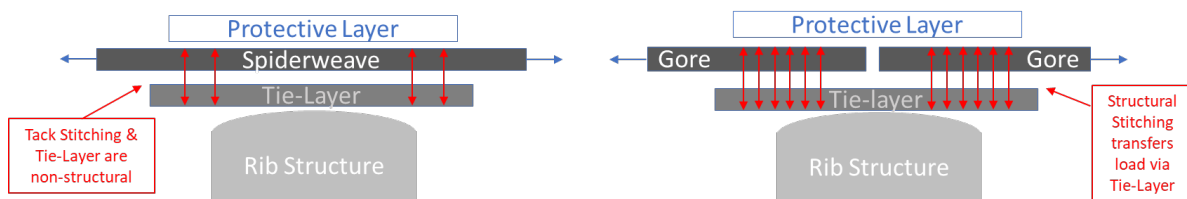


Fig. 2 End-view of Spiderweave and Stitched Joint construction style.

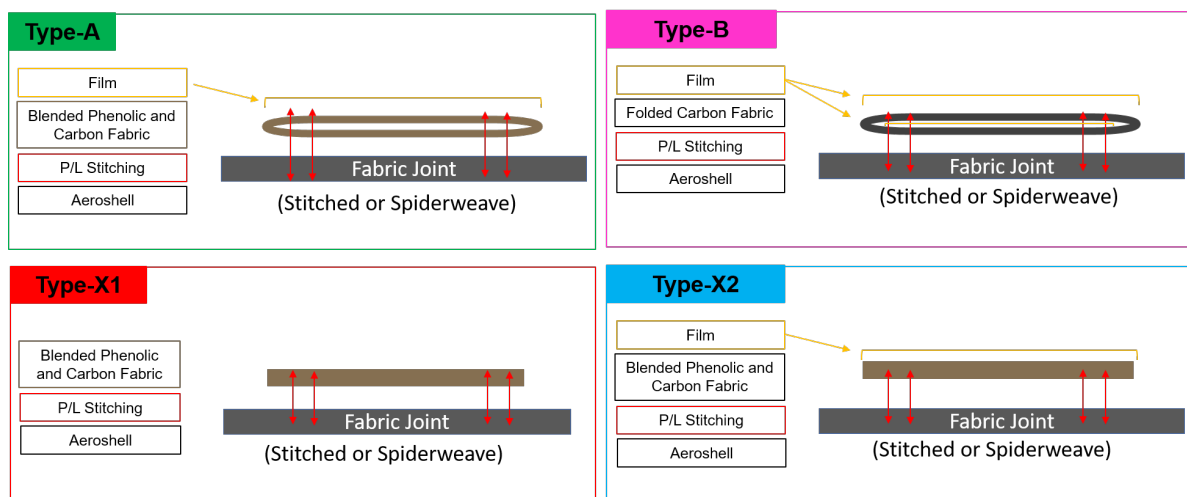


Fig. 3 End-view description of protective layer treatments applied to fabric joint.

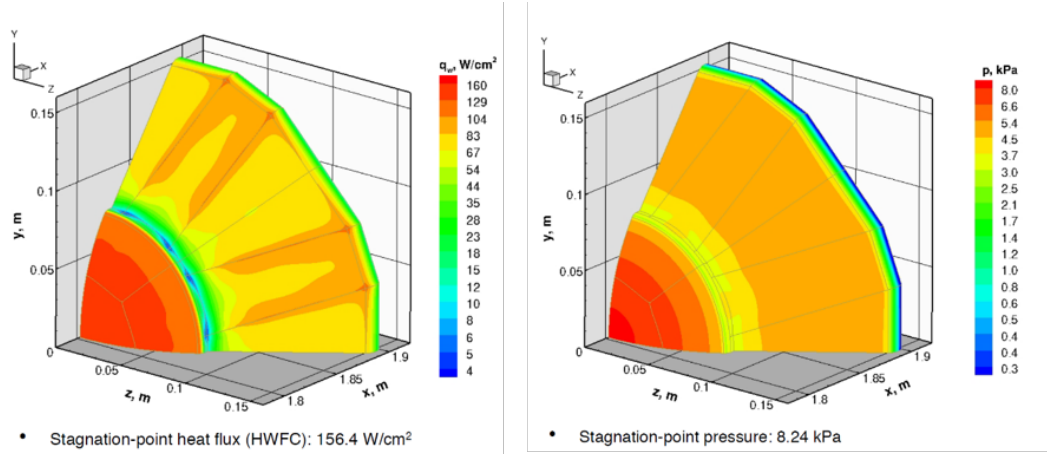


Fig. 4 Pre-test CFD predictions of the model surface quantities (quarter symmetric): hot-wall heat flux and pressure.

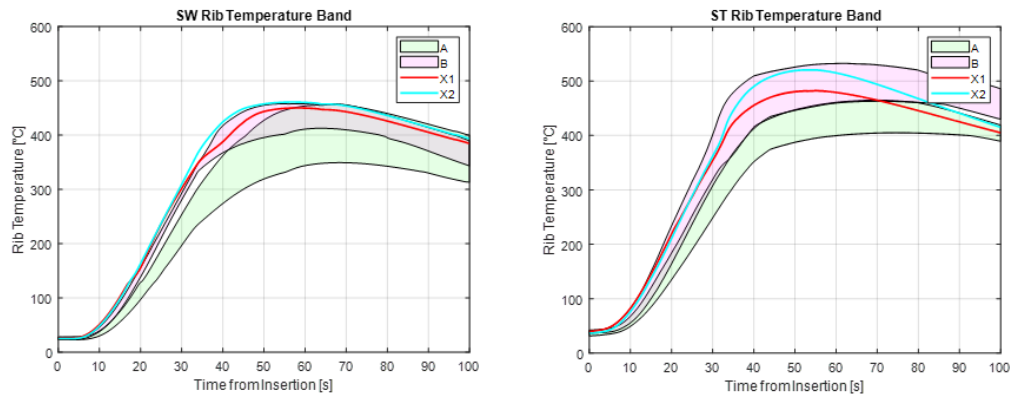


Fig. 5 Rib structural thermocouple response for Spiderweave (left) and Stitched Joint (right) articles under each protective layer treatment. X1 and X2 thermocouple traces do not have bands as only one thermocouple was applied to the Type X- region for each article.

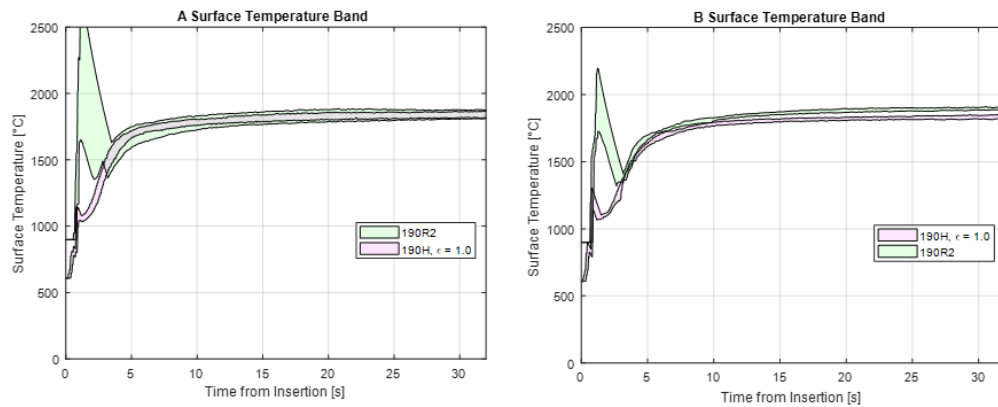


Fig. 6 Rib protective layer surface temperature measurements for Type A (left) and Type B (right) for all test articles. Pyrometer 190R2 is a two-color pyrometer with no emissivity-ratio correction applied.

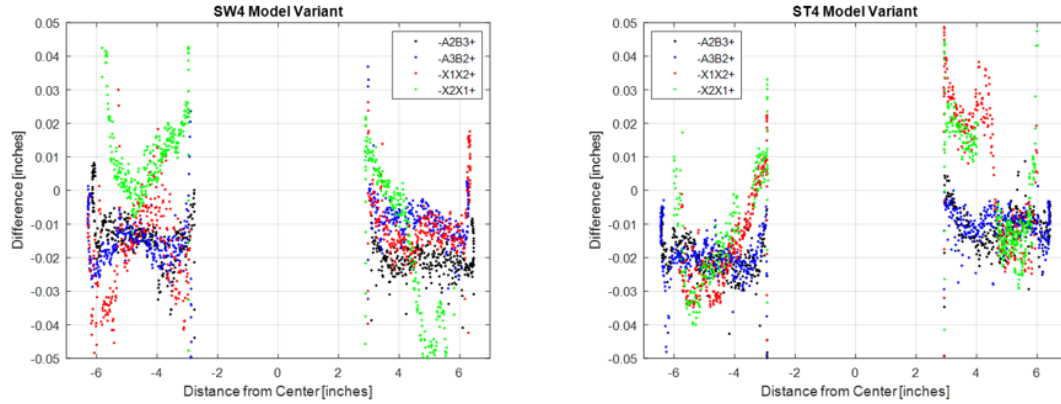


Fig. 7 Test article deformation differences for Spiderweave (left) and Stitched Joint (right) models tested in Run 4.

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