LIGHT WEIGHT INTERCONNECTION WEAVE FOR SPACE PV

Tom Borgers[1], Jozef Szlufcik, Manuel Van den Storme[3], Guy Van den Storme[3], Christian Brandt[2], Donato Girolamo[2], Shumit Das[2], Julo Verdonck[5], Philippe Nivelle[3], Jonathan Govaerts[1], Geert Doumen[1], Luc Vastmans[1], Sander De Vrieze[6], Eszter Voroshazi[1], Jef Poortmans[1]

1: imec (Partner in EnergyVille)/Thor Park 8320 B-3600 Genk, Belgium 2: ESA/Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands 3: VdS Weaving/De Bruwaan 16 B-9700 Oudenaarde 4: UHasselt (Partner in EnergyVille)/Thor Park 8320 B-3600 Genk, Belgium 5: Thales Alenia Space Belgium/Gaston Geenslaan 9 B-3001 Heverlee, Belgium 6: Centexbel/Technologiepark 70 B-9052 Zwijnaarde, Belgium

ABSTRACT: This work reports on the first results of a new concept for a flexible blanket based on weaving technology, which could potentially be employed as a carrier structure for the photovoltaic assembly (PVA) within a flexible solar array (SA) architecture. Though further away from current proposed solutions, the promising potential of such a weaving approach is describing the creation of an electrically functional and integrated flexible carrier with minimal weight and stowage volume.

Keywords: Solar Array, GEO, Solar Cell Assembly, weave, conductor integration, weaving, flexible blanket

1 BACKGROUND

The ever-existing need for developing high reliability low-cost products for space applications could pave the way for developing concepts of modular PVA systems. This technology can be applied to e.g., communication satellites or other electrically powered Geostationary Earth Orbit (GEO) applications.

The trend towards higher power demands, e.g., due to electrical propulsion, implies increasing the power demanded from the solar array through increasing solar array size and/or efficiency. With state-of-the art solar array (SA) concepts based on rigid panel substrates, only a limited size increase is possible due to mass and mechanical limitations and especially due to stowage volume constraints. To tackle this, several flexible deployable solar arrays are introduced or in development. [1] [2] [3]

Important parameters for Photovoltaic powered generators are specific power (W/m²), stowage volume efficiency (W/m³) and the structural mass of the system. Moreover, material compatibility to GEO in-orbit conditions, such as radiation, temperature etc., is crucial to guarantee long-term operation and reliability. Important aspects for cost reduction are materials and manufacturing cost and the level of automation during production and assembly; the increasing demand for powerful solar arrays is translated in an increasing number of proposals and ideas for low-cost solar array development and innovations.

Figure 1: Example of a rollable SA (ROSA) [3]

The main goal of the activity is to demonstrate the use of technical textiles as a cost-efficient, rollable, integrated, functional and light-weight carrier substrate for flexible PVAs and explore its electrical and mechanical functionalization. Through material characterization, design, and weave prototyping, the integration of the electrical cable network and support features in a flexible weave will be investigated. Besides the flexibility and adaptability of textiles to high performance and low-weight requirements of the PVA, they potentially come with a cost advantage due to the limited material diversity use, and integrated fabrication method.

2 MODULAR SOLAR ARRAY APPROACH

The proposed woven weave, with a width of minimum that of an SCA string, up to that of the solar array, a maximum length defined by the solar array, functions simultaneously as carrier substrate for Solar Cell Assemblies (SCA), the electrical circuit structure, and the mechanical support solar array blanket. This results in an integrated PVA weave that can be assembled directly to a mechanical solar array carrying structure, while directly integrating the wiring into the weave. Multiple blankets could be connected mechanically and electrically to form a large solar array integrated weave to create the total desired size (and power output) (Figure 2). Such integrated weave modules could be employed within rollable or foldable flexible solar arrays.

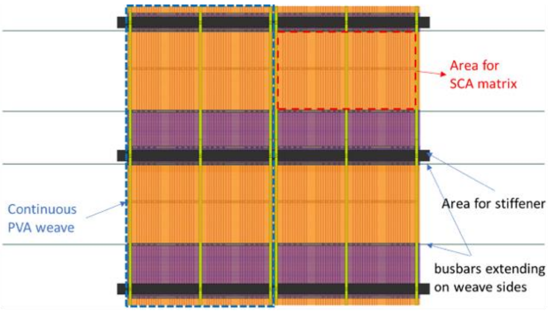

Figure 2: Modular integrated PVA weave

The goal of this structure is to improve structural weight and stowage volume of the solar array, while simultaneously improving reconfigurability, potentially reducing total cost, and still allowing automated SA manufacturing processes. Aim of the activity is to optimize the material selection for GEO environment compatibility and aim to reduce the number of materials in order to increase reliability.

3 MATERIAL SELECTION AND EVALUATION

A basic evaluation of materials used for this weaving concept is required to ensure compatibility with the operational environment. Therefore, a test group of yarns was pre-selected based on their material properties and potential resistance to GEO radiations.

Pre-screening tests of the yarn materials (8 materials in total) under reduced test regime included (half fluence) electron- and proton-, and (100 ESH) UV- irradiation. The evaluation was done through visual inspection and tensile testing based on the EN ISO 2062 (2009) standard. Additionally, static shrinkage tests were performed on non-aged yarns; limited shrinkage might be of importance to reduce stress on the SCA's after gluing, or sagging of the weave in the SA structure.

A short overview of the visual and tensile results of the tested yarn materials is listed in Figure 3 and Table 1.

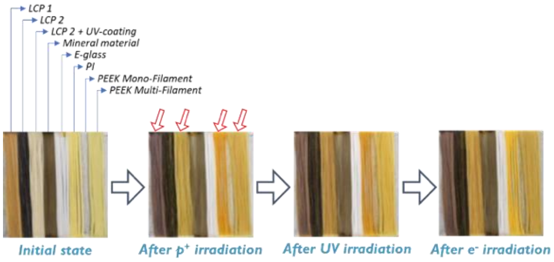

Figure 3: Visual evolution of test yarns during reduced regime irradiation test

Color darkening was observed for the Aramid, LCP (Liquid Crystal Polymer) and multifilament PEEK yarn after proton irradiation (indicated by the red arrows, Figure 3). No additional changes were noticed after further UV and then electron irradiation.

Table 1: Yarn tensile- and shrinkage test overview

	Aramid	LCP	LCP + Coating	PEEK multi	PEEK mono	PI	Mineral material	E-glass
Initial avg. Max. Load	29986	38690	38506	45359	598	2801	7604	6220
Initial avg. tenacity at Max. Load [cN/Tex]	186.97	231.68	230.58	276.58	46.33	26.35	50.69	44.97
Avg. tenacity at Max. Load after aging (% of initial)	56.83	13.51	8.88	7.07	57.25	**64.89**	**71.28**	249.41
Shrinkage (non-aged yarns) at 180 °C (%)	-0.12	0.06	0.02	-0.08	4.42	0.17	0.31	-1.47

Both LCP yarns and the PEEK yarn experienced considerable mechanical degradation; however, the PEEK monofilament yarn performed considerably better than its multifilament counterpart. The Aramid-based yarn performs better keeping 57% of the initial tenacity at maximum load after ageing. PI yarn appeared to be the best performing polymer-based material based on remaining tenacity (cN/Tex) at maximum load after aging (65% relative to initial value).

The ageing tests had less influence on Glass fibre and the mineral fibre material. However, in terms of initial tenacity at maximum load, this last material outperformed the E-glass fibre. The mineral material still retains 71% of its tenacity at maximum load value after ageing, with no degradation in Tensile strain at maximum load. A possible hypothesis of the maximum load degradation might be related to the sample preparation (fibre damage of on the sample holder). The estimated tenacity values of E-glass are very unlikely; seen the initially better performance of the mineral material, E-glass is not considered in the further development.

Static shrinkage tests on non-aged yarn samples at 180 °C revealed no large variations between the different materials except for monofilament PEEK showing much more shrinkage. This might be related to the production method (extrusion) and relaxation of the polymer at high temperature.

A basic representative test weave of the best performing polymer-based yarn (PI) and mineral-based yarn was prepared and tested according to following test cycle:

- Electron and proton irradiation at 2 energy levels, total fluence
- UV irradiation 1500 ESH

Intermediate visual inspections, and thermo-optical measurements were done before and after irradiation tests (Figure 4).

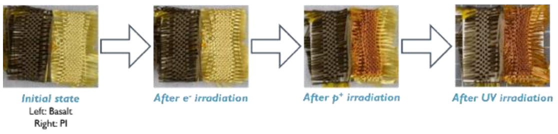

Figure 4: Visual evolution of test weaves during irradiation tests

Although no visual effects were noticed after electron irradiation on both materials, the PI sample showed waving, discoloration and became fragile and hard to manipulate after proton- and UV irradiation, in contrast to the mineral material sample.

Table 2: Thermo-optical measurements

Sample	Absorbance		Emissivity	
	Initial	After irradiation	Initial	After irradiation
PI	0.38	0.59	0.92	0.92
Mineral material	0.83	0.81	0.95	0.94

Thermo-optical measurements revealed no change in emissivity for both samples, however absorbance changed for the PI sample (Table 2).

Table 3: Tensile test results on aged weaves

		Mineral material	PI
Yarn max. load [cN]	*Non-woven, non-aged yarn*	7604	2801
	yarn from non-aged weave	7468	2469
	yarn from aged weave	4741	978
Weave Max. load [N]	*non-aged*	507	181
	aged (calculated)	310-316	63-72

A tensile test comparison with non-aged weave samples was foreseen on the aged weave, but unfortunately, the sample turned out to be damaged and frayed by handling and mounting to be employed in further mechanical testing. Therefore, tensile tests were performed on individual warp yarns of the aged weaves. Based on tensile measurements and a comparison with tensile tests on non-aged weaves of both materials with the tensile test results of non-woven and non-aged yarns and non-aged warp yarns from a weave (calculated to a similar number of warp yarns as used in the tested weaves), an estimated maximum load for both aged weaves were calculated (Table 3). These estimated weave residual strengths after irradiation revealed that the mineral material-based weave preserved 62 % to 65% of the non-irradiated weave strength (507 N). The aged PI-based weave only retained 35 % to 40 % of the non-irradiated weave strength (181.0 N). From the tests it was observed a change in mechanical behavior of the material after irradiation suggesting a material embrittlement after irradiation.

4 PVA WEAVE TESTS

From these aging test results, a passive (electrically non-functional) PVA weave design was created with respect to the different requirements and restrictions of the SA design and environment, based on the mineral yarn material. A symmetric weave style was selected, suitable for adhesion of the SCA strings. UD-tapes (unidirectional tapes), working as load carrying elements and attachment points for the PVA, are embedded in the two outer sides and in the middle of the warp (Figure 5, Left). These tapes combine continuous carbon fibres in a matrix of polymer resin resulting in a combined composite CTE resembling that of typical carbon fibre structures avoiding waving and sagging of the PVA structure. The resin allows lamination during post-weave processing. The tapes are combined to weft-oriented UD tapes to create an interwoven reinforcement harness: after lamination wherein the yarns crossing the tapes are embedded in the tape resin, the resulting weave features a UD-tape “harness”; it could be used to suspend the weave between interfaces of solar array structures.

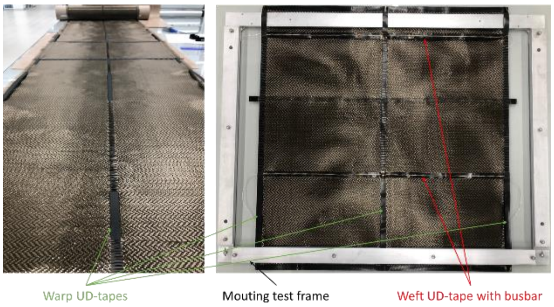

Figure 5: Left: continuous weave after weaving **Right:** Passive PVA weave mounted in test frame

5 ELECTRICALLY FUNCTIONAL PVA WEAVE

Following up on the experience from the passive weave tests, an active weave is developed, adding electrical functionality. All production methods developed for the active and passive weave are developed with automated PVA fabrication in mind, together with an industrial weaving company.

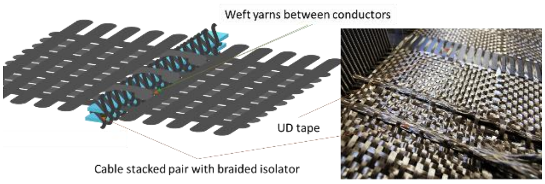

Figure 6: Detail of braided cable pair integrated in weave

The smart 3D-woven weave interweaves conductive cables and insulative yarns. The yarns provide the mechanical integrity and a carrying base for the SCA strings, simultaneously ensure electrical insulation where needed, and alignment of the cables. As in the passive weave, additional weft-oriented conductors are foreseen for string busbar interconnection. The conductors in the warp direction have an electrically insulating braided yarn jacket with a metal flat-braided ribbon core. These cables allow electrical interconnection of the PVA busbars to the solar array power management and convertors at the base of the solar array.

When a specific braiding density for the cable jacketing is used, the inner conductive braided core is still accessible by solder that is liquefied during the solder reflow process; hence the braided jacket allows selective interconnection of busbars and cables: when the weft PVA busbar ribbon is crossing over the warp cables, no electrical contact is created unless a solder joint is created through the pores of the braided cable jacketing (Figure 7); This potentially allows a soldered interconnection without locally having to remove the isolative jacketing from the cable.

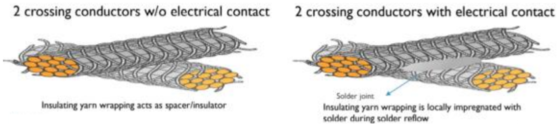

Figure 7: Cable and/or ribbon interconnection through braided isolator

A potential additional advantage of using a braided cable structure might be its ability to compensate excessive material CTE differences between different materials and components; the 3D-oriented strands and fibres allow a high degree of flexibility and stretch allowing the cable to accommodate dimensional changes during thermal cycles. Limiting material diversity by using the same material for cable jacketing and the weave reduces the risk of material incompatibility (degradation, CTE differences) potentially increasing reliability and reducing cost.

As an example, the weave can be sized to accommodate a matrix of 4 strings of 4 SCA’s of standard 6x12 cm^2 size. The design is adaptable to larger PVA sizes and different PVA configurations (Figure 8).

In the warp of the weave, between the UD tapes, warp yarns are distributed along with conductive cable stack pairs. As can be seen in figure 6, a cable stack is a combination of 2 flat braided silver-plated copper filament ribbons, covered in a braided isolative jacket from the mineral yarn (Figure 6).

Yarns are introduced in the weft during weaving, mainly in the area where SCA strings will be attached/glued on the weave in later steps, and in locations where the warp cable stacks must remain well-aligned. The weft yarns are crossing below, in between and above the cables of the warp stacked cable pairs to secure their position in the weave and acting as an extra isolative layer with the environment.

At the locations where potential SA carbon interface points are located, the warp UD tapes are not interwoven with the weft yarns, thereby selectively interweaving the warp cables and warp yarns.
As weaving is a continuous operation, this pattern is repeated. As such, the resulting weave is a continuous weave that can have a total length in accordance with the total length of the SA.

Figure 8: First version of a functional PVA weave, pictures, and details of a functional weave version

After weaving, UD tapes are placed in weft orientation, together with flat-braided conductive ribbons aligned on top of these tapes. The weave area between these two busbar ribbons is foreseen for gluing of SCA strings. During a lamination step, the warp (interwoven) UD tapes will embed all weft yarns and UD tapes that are crossing, in the resin of the UD tapes. The resulting structure creates a frame (harness) of UD tapes in which the weave is suspended.
The outer electrical contact pads of the SCA string can be welded or soldered on the braided busbar; the braided busbar allows a thermally mechanical stress-free connection. Local cutting of the busbar will create the desired SCA string interconnection scheme. The busbar ends can be soldered or welded with the PVA weave-integrated braided cable pairs.

6 PVA WEAVE CLIP ATTACHMENT TO SA STRUCTURE

To attach the weave to a load carrying SA structure, a preliminary clip design was made. The advantage of this attachment system is the limited weight (0.178 g), combined with the potential to use resistant metal coatings for GEO environment and low topography. At this time, the attachment is assumed to connect to CFRP based tape springs such as described in Ref [1 to 3]. At the areas where the UD tapes are not interwoven with weft yarns (Figure 5), the UD tapes are attached to the carbon interface points of the SA structure: an opening in the tape is made through which a metal clip is pushed.

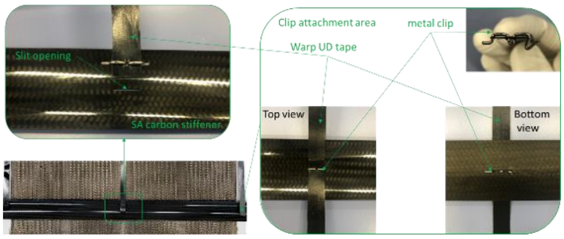

Figure 9: Detail of clip interface of weave with carbon interface point.

The clip is on its turn pushed through a slit opening in the carbon interface point of the SA (Figure 9). First tensile tests were performed on this interface by fixing the ends of 2 UD tapes, attached to a carbon interface point with a clip, in the gauges of the pull tester; a promising maximum tensile force of 200 N was reached before one of the UD-tapes was torn out at the clip area. Additional assessment of this attachment system is ongoing.

7 CONCLUSION AND OUTLOOK

In this work we report on new textile fabrics based on weaving technology that could be used as flexible carrier substrates for PVA modules that could be employed within flexible solar array architectures. We discussed first test results of prototype textiles, different functionalities and their benefits that are combined into this concept, potentially allowing for efficient, lightweight, and flexible interconnection of SCA's in different configuration architectures.

8 ACKNOWLEDGMENTS

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