WEFT-KNITTED ACTIVE JOINTS FOR SMART COMPOSITE APPLICATIONS

Q. Bollengier[1], D. Rabe[1], J. Mersch[1], E. Häntzsche[1], A. Nocke[1] and Ch. Cherif[1]

[1] Technische Universität Dresden, Institute of Textile Machinery and High Performance Material Technology (ITM), 01062 Dresden, Germany, quentin.bollengier@tu-dresden.de, https://tu-dresden.de/mw/itm

Keywords: adaptive fiber-reinforced plastics, shape memory alloys, weft-knitted fabrics

ABSTRACT

In the course of promoting sustainability through the use of lightweight structures, there is currently a high demand for functionalized fiber-reinforced plastics (FRP). In particular, adaptive FRP with both structurally integrated solid-state joints and actuators provide a high innovation potential. Conventional motion mechanisms are usually based on external kinematics with high inertia and consequently high energy consumption. Even though actuators based on shape memory alloy (SMA) can be easily processed by mean of textile techniques, only few studies use the weft-knitting technology for the realization of adaptive FRP with integrated actuators. This study presents the development and realization of functionalized weft-knitted fabrics with integrated in-situ SMA actuators interconnected with conductive yarns for the realization of adaptive FRP with integrated kinematics. After composite producing through infusion with a thermoset resin, the functional properties of adaptive FRP were characterized and evaluated. In summary, this study highlights the suitability of the weft-knitting technology for the integral manufacturing of functionalized reinforcement fabrics with integrated in-situ actuator networks for the realization of adaptive FRP.

1 INTRODUCTION

Functionally integrated, active and precisely deformable FRP have steadily gained in importance in recent years for increasing performance and energy efficiency and are a promising alternative to differential designs made of conventional isotropic metal-based materials. Such mechanisms are usually very space-extensive, hardly suitable for lightweight construction and require a linear coupling of several flexure hinges and decentralized driving mechanisms with high energy consumption. In contrast, adaptive structures with integrated actuators, that enable specific modifications of their geometrical shape and physical properties (e.g. stiffness), offer a great potential to overcome these drawbacks. Therefore, the mass inertia and thus the energy consumption of such kinematic systems can be significantly reduced and the dynamics of the whole system can be considerably increased.

Due to their higher energy density (approx. 10^7 J/m³) compared to other actuator materials such as shape memory polymers, magnetostrictive or piezo-electric materials, SMA are most suitable actuators for the development of adaptive FRP [1]. They have the property of recovering their original shape (so-called shape memory effect) after plastic deformation below a certain critical temperature by heating above their phase transition temperature.

In principle, several textile processes are suitable for the development of adaptive FRP with integrated SMA actuators. Numerous scientific studies have described the textile integration of SMA into reinforcement fabrics using tailored fiber placement (TFP) or weaving technology [2, 3], but only few studies have explored the advantages of the weft- knitting technology [4, 5]. In order to overcome these shortcomings, the current research at ITM is focused on the development and realization of functionalized weft-knitted reinforcement fabrics with integrated in-situ SMA actuators for the realization of adaptive FRP with thermoset matrix.

2 EXPERIMENTAL

For this purpose, functionalized weft-knitted reinforcement fabrics with integrated SMA actuators were developed and realized in a one-step-process on a weft-knitting machine. During the knitting process, conductive yarns are integrated simultaneously with the SMA actuators.

For this study, glass fiber rovings type EC17-1200-350 (PD Glasseiden GmbH, Oschatz, Germany) were used as reinforcement yarns in course and wale direction for the production of weft-knitted fabrics. The fineness, breaking force and elongation at break of the selected glass rovings are 1200 tex, 557 N and 3.78 %, respectively. In order to reduce the bending properties of the FRP in the deformation areas, a thin glass fiber roving type EC 410-PP3 (PD Glasseiden GmbH, Oschatz, Germany) with a fineness of 410 tex was used in wale direction. As stitch yarn, a glass fiber twisted yarn type EC-9 68x2 S150 1383 (Culimeta Textilglas-Technologie GmbH & Co. KG, Bersenbrück, Germany) was used in this study.

A commercially available SMA wire (SAES Getters, Milan, Italy) with a diameter of 0.3 mm and a transition temperature of 78-98°C was selected in this study, mainly due to its good processing capability on textile machines and its high contraction coefficient of approximately 4 % during thermal-induced phase transition [6]. This type of SMA wire is composed of nickel and titanium in a mass fraction of 54.8 % and 45.2 %, respectively.

As electrically conductive yarn, a steel filament twisted yarn Steel-tech® type 100 tex 93 (Amann & Söhne GmbH & Co. KG, Bönnigheim, Germany) with a fineness of 93 tex was selected in this study. Due to its lower bending stiffness compared to conventional metal wire, it is much easier to process on knitting machines, also as stitch yarn. Moreover, because of the large number of steel filaments, this twisted yarn is not sensitive to abrasion and preserve a comparatively low electrical resistivity of 60 Ω/m, even after processing on flat knitting machines with process speed of 1.4 m/s.

A flat knitting machine aries.3D technology (Steiger Participations SA, Vionnaz, Switzerland) with a gauge E7 was utilized for the production of functionalized weft-knitted reinforcement fabrics (cf. Figure 1). The weft and warp yarn density, the stitch length, the thickness and the grammage of the produced weft-knitted reinforcement fabrics are 29.2 yarns/dm^{-1}, 27.0 yarns/dm^{-1}, 13.7 mm, 1.57 mm and 956.20 g/m², respectively.

Figure 1: Flat knitting machine aries.3D technology (Steiger Participations SA)

Different variants of weft-knitted reinforcement fabrics with integrated SMA actuators were developed and realized. The variants are distinguished by the configuration of the deformation area, the anchoring of the SMA wires in the structure as well as the connection between SMA and the conductive yarn as shown in Table 1.

To ensure a free and even mobility of the SMA wires in the FRP and, thus, fully exploit the deformation capability of the actuators, it is necessary to minimize adhesion between the actuator and the composite structure. Therefore, the SMA wire was coated with a release agent DexCoat 8 (TAG Chemicals GmbH, Bischofsheim, Germany) before being processed. In order to ensure a good electrical interconnection between SMA and the conductive yarn, both conductive agents carbon black *Wire Glue* (American Science & Surplus, Park Ridge, USA) and silver varnish *Leitsilber* (Kemo-Electronic GmbH, Geestland, Germany) were used respectively and applied by hand locally on the functionalized fabrics at the connection point before infusion. The functionalized fabrics were integrally realized on the flat knitting machine (cf. Figure 2).

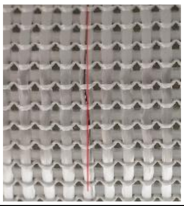
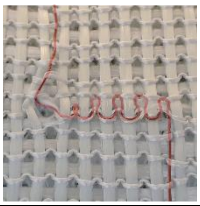
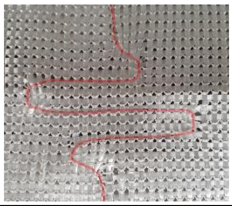
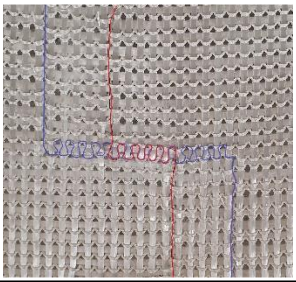
Section layout	**Section#1**	**Section#2**	**Section#3**
	rigid section	deformation area	
	8 layers, warp 1200 tex weft 1200 tex	2 layers, warp 1200 tex weft 1200 tex	2 layers, warp 1200 tex weft 410 tex
Anchoring method	**Fixation#1**	**Fixation#2**	**Fixation#3**
	without anchoring	plating (stitch loop)	zigzag
			
Contacting method	**Contact#1**	**Contact#2**	**Contact#3**
	without conductive agent	with carbon black conductive adhesive	with silver varnish
			

Table 1: Overview of the developed variants of functionalized weft-knitted fabrics for the realization of adaptive FRP (red: SMA actuator; blue: conductive yarn)

For the production of FRP, the Vacuum-Assisted Resin Infusion (VARI) process was used for the infusion of the thermoset resin-hardener system Hexion MGS® RIMR 135 and RIMH 137 (Hexion Inc., Columbus, USA) in a ratio of 10:3. It exhibits good thermal stability at elevated temperatures without significant shrinkage, which is essential, especially for thermally activated SMA actuators. In the deformation areas of the adaptive FRP, the plasticizer Hexion Heloxy® Modifier WF (Hexion Inc., Columbus, USA) was added in a ratio of 9:1 to significantly decrease bending stiffness of the thermoset matrix. After resin-infusion in the functional reinforcement fabrics, the FRP was annealed for 15 h at 50°C and then demolded for the preparation of specimens.

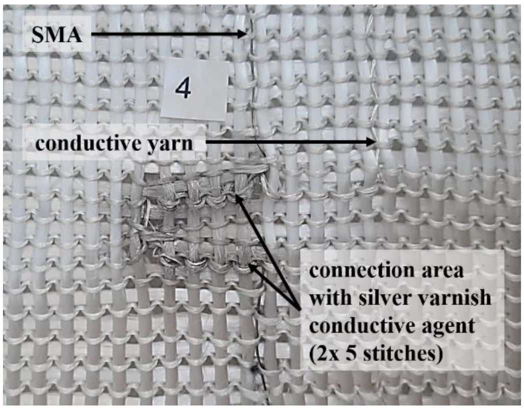


Figure 2: Weft-knitted reinforcement fabric with integrated SMA actuator and conductive yarn

For the characterization of the mechanical and deformation behavior of the adaptive FRP, tensile and bending tests were performed on a universal testing machine Z100 (Zwick GmbH & Co. KG, Ulm, Germany) considering the standards DIN EN ISO 527-4 and DIN EN ISO 14125. In order to determine which of the different anchoring methods leads to the strongest fixation of the SMA wire in the FRP, the specimens are subjected to pull-out tests. As there is no existing standard therefor, the method mentioned by Ashir et al. [7] was used in this study. A tensile testing machine Z2.5 (Zwick GmbH & Co. KG, Ulm, Germany) was used for this purpose.

Finally, to determine the best contacting method, it is necessary to test the electrical conductivity at the connection between SMA and the conductive yarn. Therefore, the surface temperature of adaptive FRP was characterized by means of an infrared camera type FLIR E95 (FLIR Systems Inc., Wilsonville, USA). A laboratory power supply unit type BT-305 (Basetech, Fürstenfeldbruck, Germany) was employed for the thermal-induced phase transition of SMA actuator via the conductive yarn.

3 RESULTS AND DISCUSSION

The results of the development and implementation of functionalized reinforcement fabrics have shown that it is possible to integrally manufacture weft-knitted fabrics with integrated SMA actuators. Thereby, the fixation of the SMA in the reinforcement fabrics and their connection with electrical conductive yarns could be directly achieved during the knitting process by different anchoring and contacting methods, as shown in Figure 2.

The results of the tensile and bending tests are presented in Figure 3and Figure 4, respectively. Compared to the rigid section (section#1), the deformation area (section#2 and section#3) exhibits both reduced tensile and flexural strength. Especially section#3 show very low flexural strength of 63.90 MPa in weft direction compared to 313.81 MPa for section#1. Hence, it can be concluded that section#3 is much suitable for the layout of the deformation area of FRP with improved deformation capability.

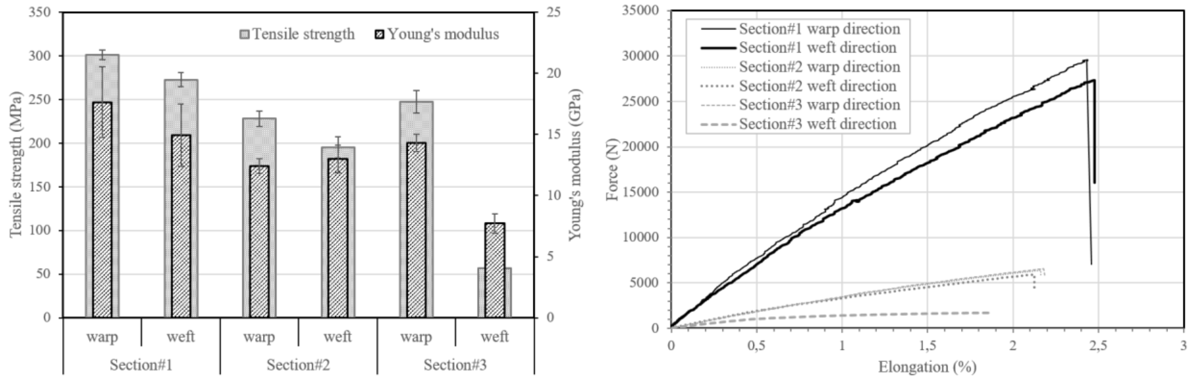


Figure 3: Tensile strength as well as young's modulus (left) and force-strain curve of FRP (right)

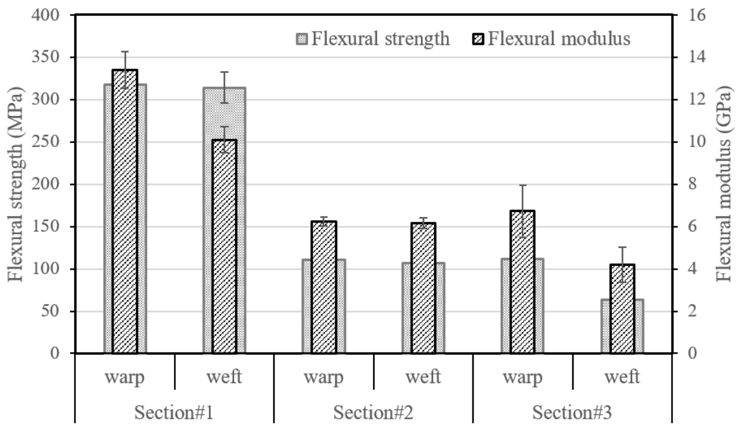


Figure 4: Flexural strength and flexural modulus of FRP in both warp and weft direction

The force-distance curve and the maximum force required to pull-out embedded SMA actuators from adaptive FRP are illustrated in Figure 5. However, for all samples the SMA broke between FRP and upper clamping jaw before being dragged out of the composite structure. Therefore, no significant conclusions can be drawn from the pull-out test. There are two main reasons for the high adhesion of the embedded SMA in FRP: primarily, the release agent used to minimize adhesion between SMA wire and composite structure is not able to assure a sufficient debonding and thus facilitate the free movability of the SMA within the FRP outside of the anchoring section. Furthermore, the embedded SMA wires are not perfectly stretched within the FRP, which leads to increased friction over the complete length of the SMA during the pull-out test, thus resulting in the breakage of the SMA beyond the sample.

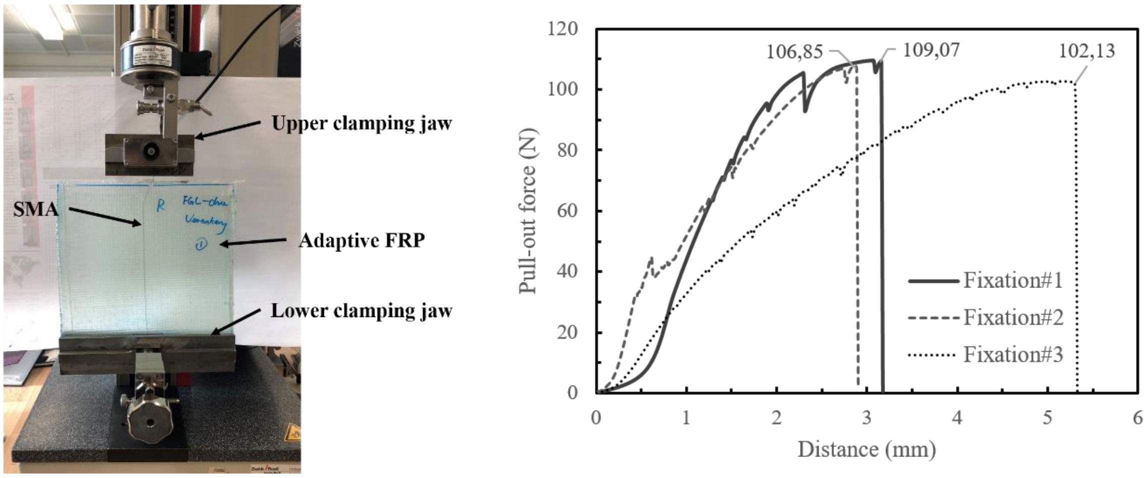


Figure 5: Test setup of the pull-out test (left) and force-distance curve (right)

The surface temperature achieved by activating the SMA actuators via the conductive yarn for different contacting methods are presented in Figure 6. The results show, that without conductive agent (contact#1) there is no reliable connection between SMA and conductive yarn. For the contacting methods with conductive agent carbon black conductive adhesive (contact#2) and silver varnish (contact#3), an increase in the current intensity from 0.5 to 0.6 A leads to a higher surface temperature, thus indicating a connection between SMA and the conductive yarn.

However, the images captured with the infrared camera reveal that the temperature of the conductive yarn in adaptive FRP is much higher than the temperature of the SMA, as shown in Figure 6 (right). This is mainly due to the large difference between the electrical resistance of SMA wires (5 Ω/m) and conductive yarn (60 Ω/m), for the conductive yarn is a twisted yarn composed of 100 thin steel filaments. Therefore, the conductive yarn is heated up quickly and the conductive agent fuses at the connection area before the SMA actuator reached its activation temperature at approximately 90°C.

	Contact#1	**Contact#2**		**Contact#3**	
Resistance (Ω)	-	25.2		22.6	
Voltage (V)		32	32	32	32
Current (A)		0.5	0.6	0.5	0.6
Temperature (°C)		80.0	108.0	48.3	65.0

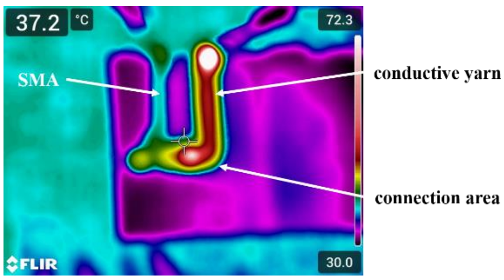


Figure 6: Electrical resistance as well as surface temperatures achieved for the different contacting methods and example of temperature distribution at the interconnection between SMA actuator and conductive yarn in an adaptive FRP with Contact#3 (right)

4 CONCLUSIONS

The main goal of this study was the development of functionalized weft-knitted fabrics with integrated in-situ actuator networks for the realization of adaptive FRP. Therefor, functionalized reinforcement fabrics with integrated SMA actuators were developed and realized in a one-step-process on a weft-knitting machine. During the knitting process, conductive yarns were integrated simultaneously with the SMA actuators. Thus, both a strong fixation of the SMA wire within the reinforcement fabric and its electrical interconnection with the conductive yarn are realized through plating during the stitch formation process.

Subsequently, FRP were realized by means of a thermoset resin infusion in the functionalized weft-knitted fabric. At last, the mechanical and functional properties of adaptive FRP were characterized and evaluated, in particular their deformation behavior by means of tensile and bending tests as well as the surface temperature in the interconnecting area during electrical powering of the SMA actuators via the conductive yarns.

Test results prove that it is possible to manufacture weft-knitted fabrics with integrated SMA actuators and conductive yarns for their powering. Since the weft-knitting technology is one of the most flexible textile processes, both a direct fixation of the SMA in the textile reinforcement fabrics as well as the electrical interconnection of the SMA actuator with electrically conductive yarns are achievable in only one process step.

The layout of FRP with reduced flexural strength and thus improved deformation capability within the deformation area is also achievable. However, solutions are required for the minimization of the adhesion between SMA actuator and FRP. Therefore, a compromise has to be found between the free movability of the SMA within the FRP on the one hand, which is necessary for the exploitation of the full deformation potential of the actuators, and a strong fixation of the SMA within the anchoring section on the other hand. Furthermore, suitable conductive yarns, which exhibit a very low electrical resistivity, are essential for the activation of SMA.

In summary, this study highlights the suitability of the weft-knitting technology for the integral manufacturing of functionalized weft-knitted reinforcement fabrics with integrated in-situ SMA actuators for the realization of adaptive FRP components.

Further works will focus on the development and fitting of appropriate simulation models for the design and optimization of highly deformable 3D active joints based on adaptive FRP.

ACKNOWLEDGEMENTS

The IGF research project 21969 BR of the Forschungskuratorium Textil e.V. is funded through the AiF within the program for supporting the “Industrielle Gemeinschaftsforschung (IGF)” from funds of the Federal Ministry for Economic Affairs and Climate Action on the basis of a decision by the German Bundestag. Financial support is gratefully acknowledged.

REFERENCES

[1] D.C. Lagoudas (Ed.): Shape Memory Alloys – Modelling and Engineering Applications. Vol. 1, Springer, 2008. – ISBN 978-0-387-47685-8.

[2] M. Ashir, J. Hindahl, A. Nocke, C. Sennewald and Ch. Cherif: Development of adaptive pleated woven fabrics with shape memory alloys. Textile Research Journal 89(2019)12, pp. 2330-2341 (DOI: https://doi.org/10.1177/0040517518792736).

[3] M. Ashir, A. Nocke and Ch. Cherif: Adaptive fiber-reinforced plastics based on open reed weaving and tailored fiber placement technology. *Textile Research Journal* 90(2020)9-10, pp. 981-990 (DOI: https://doi.org/10.1177/0040517519884578).

[4] J.I. Medeiros and R. Fangueiro: Analysis and Evaluation of Shape Memory Alloy Wires Behaviour in Weft-Knitted Fabrics. *Materials Science Forum* 730-732(2012), pp. 709-714 (DOI: https://doi.org/10.4028/www.scientific.net/MSF.730-732.709).

[5] F. Lohse, C. Wende, K.-D. Klass et al.: Bio-inspired semi-flexible joint based on fibre-reinforced composites with shape memory alloys. *Journal of Intelligent Material Systems and Structures* (2020), pp. 1-11 (DOI: https://doi.org/10.1177/1045389X20959460).

[6] F. Lohse, K. Kopelmann, H. Grellmann et al.: Experimental and Numerical Analysis of the Deformation Behavior of Adaptive Fiber-Rubber Composites with Integrated Shape Memory Alloys. *Materials* (Basel, Switzerland) 15(2022)2. (DOI: https://doi.org/10.3390/ma15020582).

[7] M. Ashir, A. Nocke and Ch. Cherif: Development and mechanical properties of adaptive fiber-reinforced plastics. *Journal of Industrial Textiles* 48(2019)6, pp. 1081-1096 (DOI: https://doi.org/10.1177/1528083718757523).