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Development of flexible matrix composites (FMC) for fluidic actuators in morphing systems

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Abstract

Purpose – This paper seeks to focus on material combinations for flexible matrix composites (FMCs) and the production methods thereof. These materials enable a high flexibility in one direction while being very stiff in the other.

Design/methodology/approach – Tested were rubber, silicone and thermoplastic elastomer matrices with carbon fibers using different production methods. These tests focused on the impregnation of the fibers with the different matrices and the orthotropy of the produced materials.

Findings – In the paper, a production capability for large quantities of easy to use off-the-shelf material was developed. The produced material handles similar to prepreg material known from “classical” composite materials. Test specimens were manufactured and characterized for mechanical properties using tensile tests.

Originality/value – These FMC materials are envisaged for a new pneumatic actuation system for an aircraft’s droop nose to replace the electro-mechanical system designed in the SADE and SmartLED projects. Combining a tube-like geometry and a variable fiber-angle lay-up enables a wide range of deformation possibilities (large design freedom of movement behaviour).

Keywords Composite materials, Elastomers, Mechanical properties of materials, Morphing structures, Flexible composites, Carbon fibers, Thermoplastic elastomer (TPE), Pneumatic actuation

Paper type Technical paper

1. Introduction

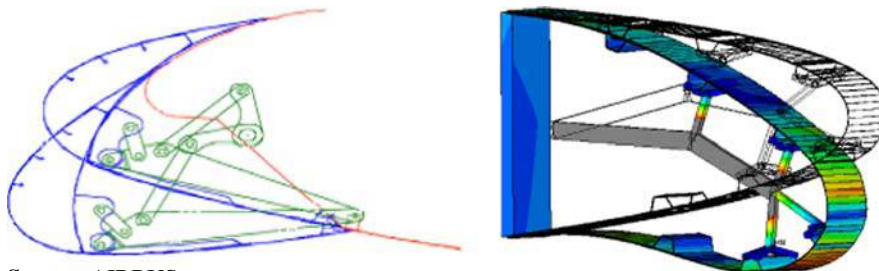
Most aircraft today are designed for a very specific flight profile and are less efficient if flown outside of that profile (Perkins *et al.*, 2004). To increase the overall efficiency (e.g. drag reduction) and to make the aircrafts more flexible in their flight profiles possibilities have to be found which enable adaptive aircrafts (and also evaluate these changes upon their impact on the overall performance) (Wittmann *et al.*, 2009). Literature presents a lot of ideas, e.g. wing-morphing in camber, span-wise or cord-wise direction and the benefits therefrom (Bae *et al.*, 2004; Cesnik *et al.*, 2004; Thill *et al.*, 2008), but the actual technology to achieve the described morphing is in most cases still missing or being developed (Philen *et al.*, 2006, 2007; Murray and Gandhi, 2007; Lan *et al.*, 2009). The motivation for this research stems from the EU FP7-project SADE (www.smr.ch/sade/)



sade_public/home.html (see Newsletter 1 and 2) and the national project SmartLED (Monner *et al.*, 2009). The aim of both projects is to create a seamless and gapless high-lift device (droop nose) at the wing's leading edge with the goal to reduce the airframe's noise and drag and enable laminar wing flow. Laminarisation is one of the technologies which can significantly reduce drag and is also within the scope of today's capabilities (Saeed *et al.*, 2009). On today's passenger-aircraft, the gaps between the wing's main box and slat and flap and also the rivets lead to a turbularisation of the flow. Therefore, among others a way has to be found to eliminate the gap between the static wing part and the active parts, which leads to a recombination of the two previously separate structures and requires a new skin and a new set of actuation methods for this new "morphing" structure. The skin in the region of the leading and trailing edge has to be flexible enough to enable the required deflection and the actuation system has to, apart from moving the structure, stabilise the skin enough to fulfil the requirements for a laminar wing (e.g. surface quality).

1.1 Actuation system

Both actuation systems developed in SmartLED (National project) and in SADE for the droop nose are highly complex electro-mechanical systems (Figure 1 (right) and Figure 2), which require a lot of very complex parts. Also due to shape and surface requirements two "actuation-stations" are needed for every meter of span. During the development, the need for a radical different actuation system arose, this led to the idea to develop a pneumatic actuation system. The goal is to reduce the systems complexity (in comparison to the mechanical system) and also a better support of the skin. This pneumatic system is planned to consist of several separate and independent "tubes" and "tension belts" (Figure 3). The tubes will have varying cross-sections from circular to elliptical, and will in part be separated by tension –carrying "belts". The maximum deflection needed is up to 20 cm, the pressure-range will be in the low-pressure range (max. 10bar). To avoid hysteresis effects of the matrix material the maximum strain will be limited to 10 per cent. To use tubes as actuation devices the wall-material has to be flexible enough to allow a certain degree of deformation (depending on the intended use), but if used (secondary use, to carry loads) as a structure, as in this case, also needs a certain stiffness. At first glance, these two requirements stand in conflict with each other, but there are several composites or special geometries that fulfil them: some examples are corrugated sheets (Yokozeki *et al.*, 2005), flexible matrix composites (FMC) (Peel, 1998; Shan and Bakis, 2005, laboratory setting) or adaptive selectively-deformable structures (Amiryants, 1998). Corrugated sheets and adaptive selectively-deformable structures are very limited in their design given by their selected geometry and also need



Source: AIRBUS

Figure 1.
Comparison standard
droop nose actuation
system (left^a) vs new
SADE Droop Nose concept



Figure 2.
SADE mechanical
actuation system

Source: DLR/Dr Heintze (Wissenschaftstag 2010, Realisierung einer formvariablen Droop Nose)

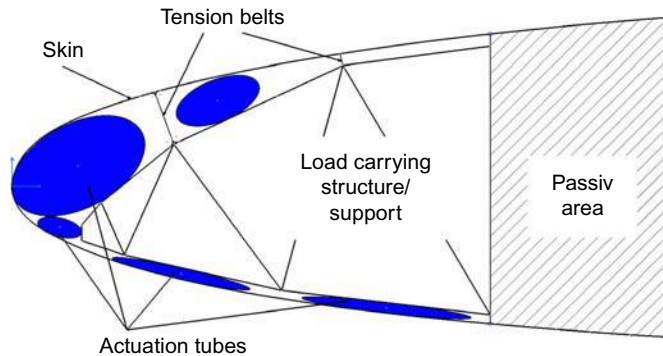


Figure 3.
New proposed pneumatic
actuation concept

some sort of flexible material to work properly. FMC on the other hand are a material with a wide field of application as they are not as restrained by their inherent structure. In the widest sense, FMC can be found in quite a few places in every day life, e.g. escalator hand rail (Keun and Schulte, 2006), car-tires, inflatable boats, etc.

In the above mentioned FMCs the fiber-volume-fraction is rather low (hand-rail, rubber-tire) or the fibers are in weave form (inflatable boats). However, the actuator concept envisioned in this study requires also a dependable and customisable fiber-layup and -orientation, as the system is planned to in part depend on the coupled-deformation response of asymmetric and unbalanced laminates, and also on varying wall-thickness, as shown in Figure 4. The coupling of the deformation has to make sure, that the laminate is only easily deflected in the wanted direction and offers a certain degree of resistance in the other directions; this will also depend on the interaction between the different tubes. All these facts led to the development of our own

production capability and evaluation of the produced material. The evaluation of the material will be discussed in this paper in detail and will focus on the impregnation of the fibers with matrix, a homogeneous fiber distribution, a reproducible and orthotropic fiber placement and the characterization of the material for FE-modelling. The FE-model will then be used to design the shape and lay-up of the actuators.

2. Required material properties

Based upon the above mentioned requirements, material considerations and the research done by Shan *et al.* and Peel the choice of material for the actuation “tubes” fell on FMC. These materials are continuous fibers impregnated with a flexible matrix material. In the referenced papers and works several possible production techniques were mentioned and researched, but all remained in a laboratory setting. As the afore-described actuation system is planned for a future passenger-aircraft a material combination with a process which can be better automated process has to be found. Also a material with good handling qualities similar to, e.g. carbon-fiber prepreg would be preferable. Based on these preliminary constrains several possible materials for matrix, fiber and several production processes were preselected. As matrix material several types of material came into consideration, such as natural rubber, silicone rubber and thermoplastic elastomers (TPE). Each matrix material comes with wide variety of properties, but the foremost requirement for this study was that the matrix material could be liquefied enough to impregnate the fiber material thoroughly. Based on experience a viscosity of 100 mPa*s or less is needed to successfully impregnate dry fiber material using the standard infusion techniques (e.g. vaccum infusion process).

2.1 Material combinations

For this research several material combinations were tested, see Table I. Experiments with glass fibers were halted early on as their behaviour (during the tests) was

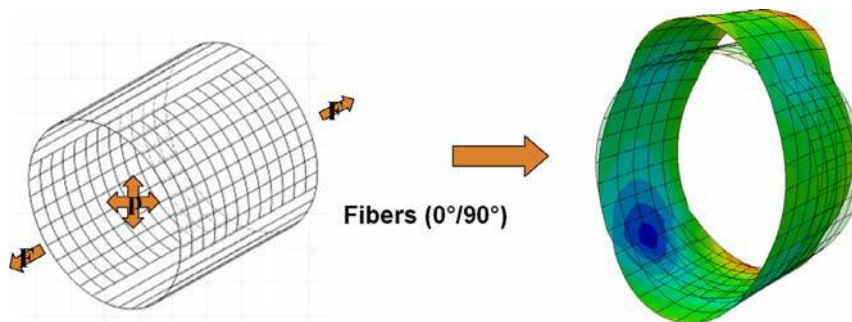


Figure 4. Tube segment; unsymmetrical lay-up and deformation-response under load (example)

	Fiber material	TPE	Matrix material	
			Rubber	Silicone
Carbon fibers	Single rovings	X	X	
	UD-Tape	X	X	
	UD-non crimp fabric	X		
Glass fibers	Multiaxial-weave	X		X
	Multiaxial-weave	X		X

Table I. Tested materials

comparable to carbon fibers. From first test, it was concluded that they would behave similarly in a manufacturing process to carbon fibers in other tests and would therefore be redundant. Also do carbon fibers offer a much higher stiffness to weight ratio than glass fibers which makes them more interesting to use in the long run. The tests for each matrix material were usually conducted with a variety of carbon fiber materials to determine the influence of different grammage.

As can be seen in Table I, not all matrix materials were tested with all fiber materials. The reason for that is, after the first experiment, it could usually be seen if further tests and which grammage would deliver best results.

2.2 Production techniques

One goal of the research was to find a technique to produce large quantities of FMCs in an easy and reliable way. For this purpose several methods were looked at, some of them unique to certain material-combinations as the flexible matrix materials have different handling requirements, e.g. rubber has a too high viscosity for vacuum assisted process. Also silicone and rubber are usually cured at elevated temperature and are after that no longer mouldable. The temperature needed to achieve a low enough viscosity speeds up the solidification and, therefore, time-consuming or long-duration processes are not an option, neither is producing a semi-finished part (wrought material) possible with these materials and production processes.

3. Material production trials

All experiments for the production trials were conducted with regards to the grammage of the fiber material and the results of the first test. For example, the first experiment with rubber and carbon fiber-12k-roving resulted in the conclusion that the fiber-material was much too thick a much lower grammage was used in the following experiment.

3.1 Rubber (SBR)

For preliminary tests single fiber-rovings (Torayca FT 300B 6000 50B) were pressed onto rubber sheets (SAA1052/70) to try to impregnate the fibers with the rubber and create a compound, which quickly showed that it was necessary to spread the fibers as thin as possible, due to the relatively high viscosity of the uncured rubber. Therefore, all following tests were conducted with the material-combination of Dynanotex HS 15/50SL carbon fiber-tape as fiber material and the rubber mixture SAA1052/70 as matrix material. Owing to the fact, that the viscosity of the rubber at 90°C was still very high and the rubber foil only available at 0.5 mm thickness, it was necessary to repeatedly double/fold the press-result to achieve a balanced distribution of carbon fibers in the rubber matrix. Also through the multiple pressing more than half of the original amount of rubber was pressed out of the tool and increased the fiber volume fraction.

3.1.1 Experiment description. The UD-fiber-tape and the rubber foil were pressed together at 90°C and a beginning pressure of 250bar for five minutes. The resulting sample was cut in the middle, stacked and pressed again to receive in the end an eight-layer strong laminate. The pressure during the experiment was progressively raised from the 250bars in the beginning to 400bars in the end. Afterwards the laminate was cured at 140°C and 120bar for ten minutes. This laminate had a resulting thickness of 0.4 mm. In total, this process was repeated three times resulting in total in two eight-layered laminates and a 12-layered laminate.

3.1.2 Conclusion rubber testing. Trying to press rubber into the fibers using high pressure (250-400bar) worked very well, as far as the distribution of rubber in the fiber is concerned. As can be seen in Plate 1, the flow of the rubber led to a high distortion of the fibers, making it impossible to create an orthotropic material. Concluding it can be said that pressure molding is not suitable for producing unidirectional FMCs with a rubber matrix. The other production methods were not feasible (VAP) or not available (pultrusion) for testing.

3.2 Silicone rubber

Tests with various silicone materials were conducted in previous in-house studies with varying results.

The investigation of silicone as a matrix material for this paper was conducted mostly as a literature research and only some very small experiments were performed. Tests for this paper were conducted using a two component silicone and a bi-axial carbon fiber, see Table I.

3.2.1 Experiment description. In the experiment, the carbon fiber was simply hand-laminated with the two-component silicone Elastosil LR 7665 from Wacker at room temperature and then cured at the specified temperature. The silicone proved to be too viscous to flow in-between the fibers and simply formed a layer on top and on the bottom of the laminate.

3.2.2 Conclusion silicone testing. It quickly became apparent through the literature research, that most silicone materials have a too high viscosity to properly infuse the fiber materials. The above described experiment led to the same outcome. No further experiments were conducted with different fibers, as the results did not promise more success with a thinner fiber material. There are only some very specialized silicone materials (e.g. Wacker Elastosil S 690 or S 692), which theoretically have a low-enough viscosity, but these silicones are very expensive and, therefore, not preferred for producing a large quantity of material.

3.3 Thermoplastic elastomers (TPE)

The third matrix-material to be investigated was TPE. TPE has in other studies proven to be viable as matrix materials for dynamically loaded FMC (Keun and Schulte, 2006). TPEs are available in a wide variety regarding hardness, temperature range and mechanical properties.

Preliminary tests were performed at KRAIBURG TPE and EADS innovations works in parallel to the two other matrix materials described above. These preliminary tests resulted in a much more intensive investigation of the TPE in combination with



Plate 1.
Rubber (SBR) pressed into
fibers at 250-400bar at
KRAIBURG Gummiwerke

carbon fibers. TPE was the only matrix material to be tested with all four production techniques mentioned in Table II.

One important property for these tests of molten TPE is the reduction in viscosity through temperature and shear forces. Shear-forces reduce the viscosity dramatically, as can be shown in Figure 5.

3.3.1 Preliminary tests with TPE. The preliminary testing using a pressure mould was conducted at Kraiburg TPE with poor results. In these tests, one 2,5 mm thick plate of TPE was placed on top and on bottom of a unidirectional 12k carbon-fiber fabric. This assembly was heated to 190°C and pressed at 4bar.

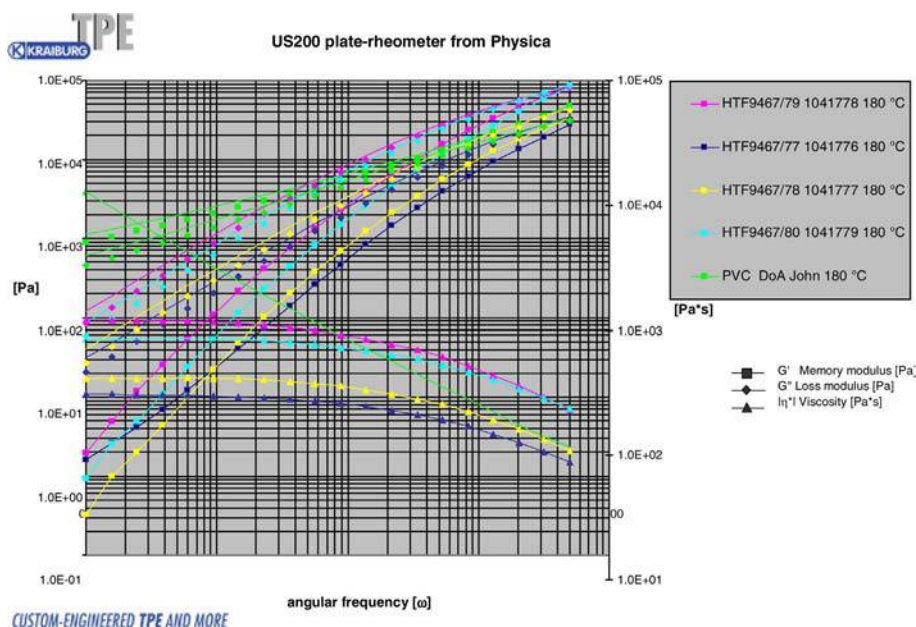
As can be seen in Plate 2, the TPE did not infuse the carbon fibers properly, but stayed on the surface of the carbon-fiber-fabric. Also probably due to the heat, resulting in outgassing, the TPE is infused with gas-pockets, further reducing the quality.

Further production trials using injection moulding produced slightly better results but also made clear, that the fibers have to be restraint during the process, as they

Table II.
Material and production methods

Production method	Hand lamination	VAP	Injection moulding	Pressure moulding	Pultrusion
<i>Material</i>					
Rubber	-	-	-	+	-
Silicone	+	-	-	-	-
TPE	-	+	+	+	+

Notes: + means tested configuration; - means not tested



CUSTOM-ENGINEERED TPE AND MORE

moved with the matrix material which resulted in a highly distorted fiber orientation. Owing to the speed of the TPE and the resulting flow the fibers at the injection-point were pushed away (Plate 3). Also the TPE did not infuse the fibers completely which was likely caused by the rapid cooling of the TPE due to the “cold” cast.

3.3.2 Preliminary tests at EADS innovation works (IW). Based on the test at Kraiburg TPE similar tests were performed at IW to find ways to improve the production process to the point of being able to produce full impregnated FMC materials with a TPE matrix.

The tests were performed on a fully automatic pressure mould with heat-able plates. These plates were heated to 180°C, the pressure was set to 2.5bar and the processing time was 30s-60s depending on the fiber-layer’s thickness. This process produced good results but also quickly showed some draw-backs and a limit for the thickness of the dry fibers to be used.

One draw-back is the amount of movement the liquefied TPE performs, as through this movement the fibers are shifted from their position and fiber undulations are created. In contrast to classic fiber-composites some change in fiber-angle has a very large impact on the mechanical properties of the resulting FMC-composite (Peel, 1998). As can be seen in Plate 4, the TPE successfully infused the fibers and created a good surface. Again the problem of the flowing of the TPE during the infusion-process becomes apparent. The fluid TPE carried fibers at the edge of the fiber material with it, disturbing the orthotropic properties. The problem becomes even more pronounced when using unidirectional fiber material.

3.3.3 TPE with vacuum assisted process (VAP). To investigate if VAP would be a viable production method for FMCs with a TPE matrix a classical VAP built-up was



Plate 2.
TPE and carbon fibers
processed in a pressure
mould at 190°C at 4bar

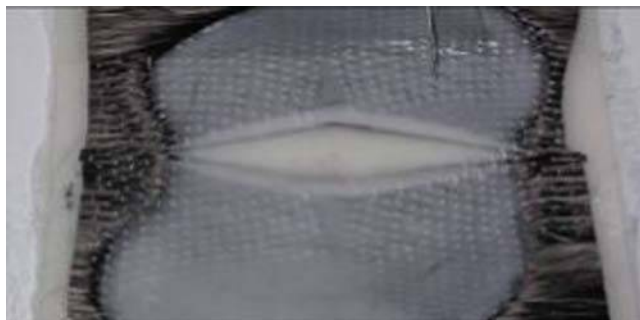


Plate 3.
Thermoplastic elastomer
injected in an
unidirectional 12k
carbon-fiber preform at
190°C in a cast at
room-temperature

Plate 4.

Two layers of
biax-6k-carbon fiber
infused with TPE at
2.5bar at 180°C

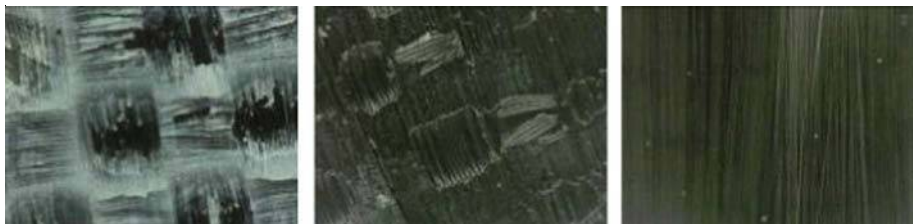


used. The preform and the matrix were heated to 180°C and then the TPE was sucked into the preform at a pressure difference of 0.8bar. The idea to reduce the viscosity of the molten TPE through the suction worked not as well as expected. The pressure difference in the VA-process proved to be too low for the relatively high viscosity (in comparison to a standard resin, e.g. RTM6) and due to the slowing of the TPE as it contacts the fibers, the viscosity reduction through shear forces is greatly reduced. Therefore, the molten TPE could not flow very far into the fiber layer. The process was very slow (>5 hours) and, therefore, the total amount of matrix infused into the fibers was very small. It could also be observed that the TPE did not bond with the fibers. The positive effect of the vacuum was, that the fibers stayed in place and, therefore, no undulations occurred and also no gas-pockets remained. The results from this trial can be seen in Plate 5, important to note is that the area of the fibers that were successfully infused had a rather high fiber-volume-fraction (of about 70 per cent) and showed good handling quality.

3.3.4 TPE pressure moulding. Pressure moulding as described above in the preliminary tests proved to be a viable production method if the movement of the fibers could be prevented. In order to achieve this, a special cast was constructed.

Plate 5.

Carbon-fibers with a TPE
matrix, after VAP (for 3h)
(left and middle) and as a
comparison dry fibers
(right)



This cast was a metal frame into which the fibers were clamped. The tests were again performed at 180°C with a variable pressure range from 1 to 2.5bar and 30s to 120s. The cast was preheated to the required 180°C.

Pressure moulding in general produced very good results with the above defined settings in terms of impregnation of the fibers. The tests showed that the cast could also not constrain the fibers completely. The results were better than without but still the fiber angle could not be set to a predefined orientation.

3.3.5 Pultrusion process. In cooperation with Jonam Composites Ltd, it was possible to produce a prepreg-like FMC through the use of a pultrusion process. A pultrusion process offers the advantage that the fibers are all oriented in the same direction and are kept under tension at all times, therefore, the above repeatedly mentioned undulations cannot or only minimally appear with this production process (Plate 6).

With the pultrusion process the FMCs were produced at a speed of 2 m/min at 180°C with a fiber-volume fraction of 50 per cent. The produced FMC is a material-combination of Torays T700S carbon fiber and the TPE-SEBS patch HTF 9471/16 from KRAIBURG TPE. The pultrusion process was used to create roughly 20 kg of TPE/carbon-fiber FMC for further material testing.

3.3.6 Combination of pultrusion and pressure moulding. Based upon the preliminary tests and the pressure moulding tests with the cast it became apparent, that the tested methods were in themselves not sufficient to create FMCs in a reliable and reproducible way. The best results were reached using the pressure mould, as the infusion of the carbon fibers was very good while using a low grammage, but the undulation of the fibers was a problem. A solution to this was the use of a pultrusion process. Pultrusion showed that it is possible to create FMC wrought material at a high speed and constant quality. Pultrusion is also a proven technology for the creation of composite pre-preg material.

4. Mechanical testing of FMC

These tests aimed at determining the mechanical properties of the material and to be able to calculate material parameters for a FE-model. The tests also help to evaluate



the behaviour of these composites under load, as the use of highly elastic/hyperelastic matrix material and large strains makes an application of classical laminate theory inaccurate. Additionally the test offers information on possible failure modes (beside max stress/strain). The prepreg material was used to produce test samples for tensile tests. The tape produced in the pultrusion process had a too high fiber volume fraction to create test specimens for the planned tensile tests. Therefore, the tape was cut into a desired shape and a 0.25 mm TPE foil was layered on top and on bottom of the “prepreg”. This stack was then combined using pressure moulding at 100°C and 3bar for 120s. As no suitable test norm exists, the test-specimens were designed based on CFRP and rubber test norms, literature research (Peel, 1998) and FE-simulations to determine the required shape. The final test-specimens were 60 mm wide, 260 mm long and between 0.8 mm and 0.9 mm thick. Tested were eight specimens each in 0°-, 90°- and $\pm 45^\circ$ -fiber angle direction. The specimens were four-layers “prepreg” material (UD-same direction) with a layer TPE on top and on bottom, resulting in a fiber-volume fraction of 28 per cent.

4.1 Tensile tests

The above described test-specimens were tested on an Instron 5566 10kN test-machine with an optical strain measurement (Laser) (continuous measurement). The test specimen were prior to the tests stored at 22°C and 40 per cent humidity for at least 24 hours and the tests were performed under the same environmental conditions. The optical strain gauge was only able to capture strain in one dimension, so the tests were also video- and photo-recorded. For this purpose, a grid was applied to the specimens to be able to measure the distortion at every point during the test and calculate the strain in a second direction (Plate 7). The tests were conducted at low enough speeds to be considered as semi-static. The 0°- and $\pm 45^\circ$ -specimens were tested at 2 mm/min, whereas for the 90°-specimens the speed was increased to 10 mm/min, after a load of 10 N had been reached.

4.2 Results of the tensile tests

As expected, the results for these tests differ largely depending on the fiber-direction. Testing in 0°-direction proved to be the most difficult, because the specimens started to slip from the clamps which led to inaccurate measurements. Thus, material failure could not be achieved and, therefore, no maximum strength was found. The test with $\pm 45^\circ$ and 90° were stopped when the force no longer increased (or started to decrease, see Figure 7) or the marker for the optical measurement left the maximum possible range. In only one case did the test-specimen fail completely (90°-rent of the matrix material). The failure behaviour of the different test specimens is summarised in Table III.

For an example of the slippage of the 0°-specimen (Figure 6). The force-strain graph is roughly linear but shows a certain unevenness. These “bumps” are due to the slippage, observed during testing.

Comparing the graphs from 0° tests with 90° or $\pm 45^\circ$ test the non-linear material behaviour of the matrix material becomes apparent (Figures 7 and 8). Interesting to note is also the difference in maximum force the samples could carry.

As the material is designed to be very flexible in one direction the deformation in that direction can become very large. To be able to calculate material response under load correctly, the hyperelasticity of the matrix-material has to be considered. In literature, there are several proven material-models to choose from for hyperelastic behaviour, e.g. Ogden (1972), Mooney-Rivlin, James-Green-Simpson, etc. depending

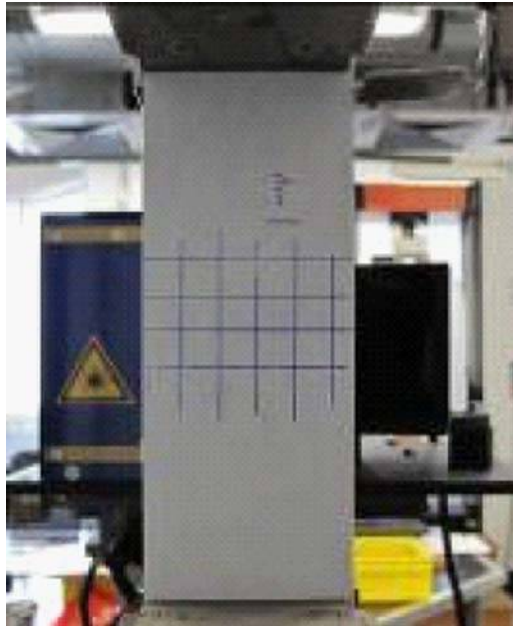


Plate 7.
Distortion-grid on
test-sample

Fiber direction (in relation to force)	0°	90°	± 45°
Failure behaviour	Delamination of the upper layer of TPE at the clamps/ clamping problem not material failure	Crack/rent of the matrix material	Delamination on the edges of the specimen

Table III.
Failure behaviour
depending on fiber
direction

on the deformation to be calculated. As FMCs are not isotropic materials, these models cannot be applied, as they demand isotropy for a complete analysis. Therefore, different models have to be used, which can be found, e.g. in biomechanics, namely the generalized Fung model (Fung, 1993) or the Holzapfel-Gasser-Ogden (Gasser *et al.*, 2006) model. These models allow anisotropic material-behaviour in connection with hyperelastic behaviour.

The tensile tests resulted in the mechanical properties of the material as can be seen in Table IV. It can be noted that the Poisson ration is (approximately) zero, an at first glance unusual result, which is probably caused by the large difference in the elasticity modulus of matrix and fiber. The matrix deforms under such small loads, that there is no measurable deformation response of the fibers.

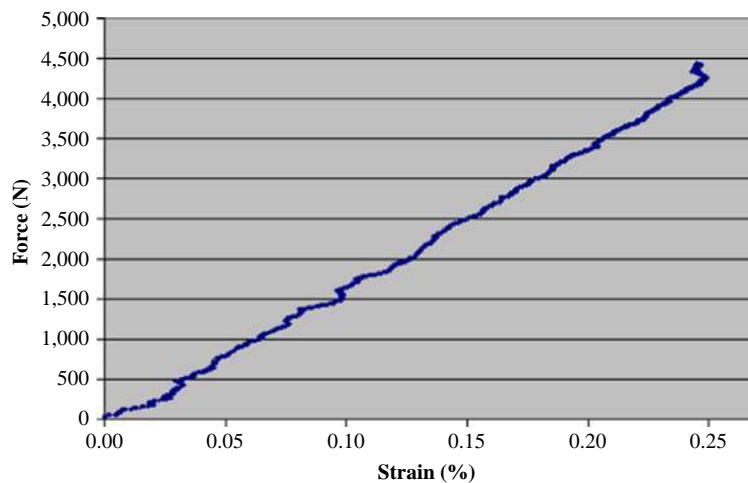
5. Conclusion

The need to develop a FMC was identified and described. The requirements ask for a stiff/flexible material depending on the regarded direction with dependable fiber direction and similar handling qualities to “classic” composite prepreg.

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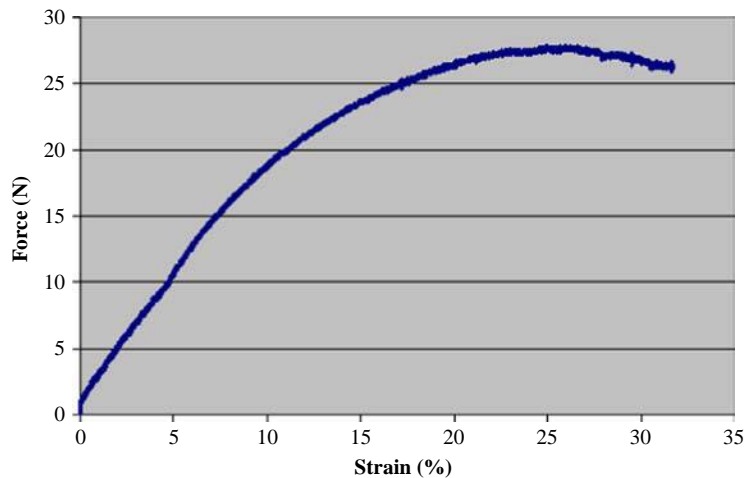
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Figure 6.
Force-strain curve
specimen #3-0°



Source: HRAIBURG TPE

Figure 7.
Force-strain curve
specimen #3-90°



Also a production method had to be developed, that could produce this type of material reliable in large quantities and time and cost efficient. In the paper, different production trials with different types of material are described.

In Table V all tested material-combinations are listed as described in Chapter 3, not every matrix material was tested with each type of fiber material. Often the first experiment delivered enough results to eliminate certain combinations.

The experiments with the various production processes and materials proved pultrusion and pressure moulding as the leading technologies to create FMC. Especially, pultrusion enables the production of a constant quality of prepreg like FMCs.

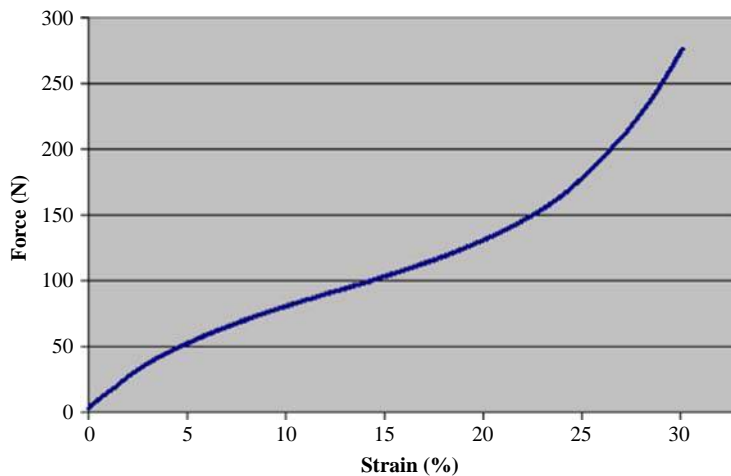


Figure 8.

For pressure moulding to become a viable production technique a way has to be found to properly restrain the fibers to avoid undulations. Even if the fiber-placement could be ensured, it would still be necessary to first create a wrought material with which the final lay-up is realized. The test with pressure moulding showed, that a too thick (above 6k) laminate could not be properly and reliably infused. Further research with the pultrusion process has to be conducted considering fiber-volume-fraction and different mixtures of TPE in order to achieve better mechanical properties. Thermoplastic elastomers in combination with carbon fibers have so far proven to be able to create FMC through the use of pultrusion and pressure moulding.

The tensile tests described in this paper were performed to understand the behaviour of the composite under load, to discover possible failure modes (beside max. strain/stress) and acquire data to simulate the material. The FE-models will be used to evaluate the different fiber-layups for the actuation tubes and help to decide the final geometry of the actuation system. The tests showed that 10 per cent strain (for $\pm 45^\circ$ and 90°) is easily achieved and sustained without failure. As long as the design of the actuation system is not finalized no answer can be given on the loads and strains seen by the actuation tubes and whether or not this specific material (values in Table IV) can successfully fulfil all requirements envisioned for the actuation mechanism. The next steps of this ongoing research will be the design of the actuation system, with it the definition of loads and the testing of prototypes.

Material properties (calculated using the test-data, only valid up to 10 per cent strain)

$$E_1 = 47481,43 \text{ N/mm}^2$$

$$E_2 = 4.24 \text{ N/mm}^2$$

$$\nu_{12} \approx 0$$

$$G_{12} = 3.49 \text{ N/mm}^2{}^a$$

Notes: ^a1, in fiber direction; 2, orthogonal to 1

Table IV.
Material properties of the
TPE-C-FMC at $\phi_f = 0.20$

Base material	Continuous fibers			Matrix material		
	Fiber type	Fabric type	Area weight	TPE ^a	Rubber ^b	Silicone ^c
Carbon fibers	Torayca T300B-6000	6k-roving	396 tex	X +	X -	
	Dynanotex HS 15/50SL	UD-tape	50 g/m ²		X +	
	Torayca T700S	UD-tape	100 g/m ²	X +		
	Torayca FT 300B 6k 50B	6k-UD-fabric	120 g/m ²	X +		
	Toho Tenax IMS65 E13 24k 830tex	24k UD-fabric	208 g/m ²	X -		
	Torayca T300B-6000	6k Biax-fabric	317 g/m ²	X +		X -
	Torayca T700S-12000	12k biax-NCF	578 g/m ²	X -		X -
Glass fibers	Interglas technologies	Biax fabric	288 g/m ²	X -		X(+)

Notes: X + : tested and success, X - : tested failure, blank: not tested; ^aTPE-SEBS Patch HTF 9471/16 Kraiburg TPE; ^bRubber SAA1052/70 Kraiburg Gummiwerke; ^cSilicone: MVQ-silicone (FSU-50-83 by MG Silikon)/Wacker Elastosil LR 7665

Table V.
Tested materials

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