New evolution
Progress in thermoplastic composites
True innovation starts new traditions. Fokker Aerostructures does just that by introducing new principles in aircraft structure technology. Most striking is thermoplastic composite assembly. At first glance a moveable wing part of this nature may be a reminder of the way in which fathers and sons put paper model kits together. The main difference with folded and glued thin cardboard is that construction simplicity and reliability in real airplane parts are achieved through advanced shaping and welding of fibre reinforced thermoplastic plate elements. The basics of assembly through folding, bending and attaching may be simple, but achieving optimal functionality in products with minimum mass is a process of considerable sophistication. It implies no less than an entirely new structural concept. The result is true composite design, far away from what is known as black metal design.
Thermoplastics in aerospace technology mainly have glass or carbon fibres for reinforcement. Occasionally it will involve polymer fibres, such as aramid, or polyethylene. Fibres can be short (chopped into bits of a few millimetres), or continuous. Polymers with chopped glass fibres can be injection moulded or thermoformed, like all thermoplastics. Continuous glass or carbon fibres always are arranged in a fabric, braid or in unidirectional tapes, to provide a maximum strength per unit density. This puts a certain limit to their formability.

**The right fibres**

**Saving materials and energy**

In aerospace economy, structural performance and ecology are quickly becoming synonymous. Fuel saving measures are paramount, and they are directly linked to both costs, weight and environmental impact. Weight reduction of 100 kg in an average airliner saves about 19000 litres of fuel on a yearly basis, with the attached CO2 and water emission reduction. Thermoplastic composites save weight. Moreover they are suitable for recycling, the importance of which began to shine through in the mid 1970's and is fully clear now. Because they maintain their formability they can be reused and separating fibres and matrix for recycling is a realistic option.

![World fleet average consumption graph](image)
The right thermoplastics

It takes time to fulfill promises. With regard to high performance applications the early thermoplastics were insufficiently resistant to heat and moisture. The first high performance composites to become available had PEEK (Poly-Ether-Ether-Ketone) as a matrix. After this first step the need grew for a more affordable material that was easier to handle in production.

Material development is a continuous process. So called “oligomers” (meaning molecules with few parts, in the middle of monomers (single parts) and polymers (the opposite of monomers for consisting of many parts), hybrid plastics, almost literally a crossover (on the molecular level) between thermosets and thermoplastics, may soon offer interesting new options. They feature low viscosity during part production but turn into thermoplastics after heating. Depending on molecular structure they can be either thermoset or thermoplastic: possibly the best of both worlds.

PEI (Poly-Ether-Imide) was next to be applied in structural parts. It was quite successful but it did have a drawback: it was sensitive to the kind of aggressive fluids that live in wide body aircraft. A better polymer had to be developed. With the year 2000 approaching this became PPS (Poly-Phenylene-Sulfide). No material is perfect for every application. PPS is widely used, but its surface energy and shrinkage behaviour leave room for PEKK (Poly-Ether-Ketone-Ketone). Currently Fokker most commonly uses the latest version of PPS, but the choice between PEEK, PEKK, PEI and PPS is fine-tuned to functional and process requirements. Affordability and weight are the determinant factors.

<table>
<thead>
<tr>
<th>mechanical properties</th>
<th>cost</th>
<th>processing temp</th>
<th>Tg</th>
<th>chemical resistance</th>
<th>bonding</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEEK</td>
<td>++</td>
<td>-</td>
<td>o</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>PEI</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>PPS</td>
<td>+</td>
<td>+</td>
<td>o</td>
<td>o</td>
<td>+</td>
</tr>
<tr>
<td>PEKK</td>
<td>++</td>
<td>o</td>
<td>o</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Summarizing structure

Thermoplastic composites are not just another family of material options. Rather they constitute a way of thinking, a complete system of producers of fibres and matrices with those that know ways to combine them.

All thermoplastic composites consist of one or more layers of fibres in a matrix. Fibre layers can be woven or consist of unidirectional tapes. Mechanical properties, such as strength and stiffness can be tweaked by optimizing fibre arrangements. Another option is spanning single fibre bundles over a surface (tow placement), or let a robot put them into place according to a non-geodesic program, which is called fibre steering. Fixing one thermoplastic coated fibre bundle with a laser, layer by layer, is where the build-up of a composite unexpectedly becomes very much akin to 3D printing, opening up new opportunities altogether. Plates can be laminated with fibres optimally oriented to deal with stress. Sharp edges, for instance the back rims of rudders are the result of folding along a straight line, but curved folds can be produced as well. Remember origami. To arrive at form (for instance a fuselage section, or a wing nose), plates are bent in a mould and the curves are fixed with ribs that are glued or, preferably, welded to them.

Ecosystem integration

Thermoplastic composites are not just another family of material options. Rather they constitute a way of thinking, a complete system of producers of fibres and matrices with those that know ways to combine them.

Its technosphere includes forming methods, principles of fastening, hierarchies of composition, production, testing and application and comes with its own options for repair. And all that happens within this fascinating thermoplastic composite ecosystem concurs with the evolvement of a software universe of tailored analysis. Integration of all these facets is not just a matter of technological fine-tuning, like it used to be when airplane manufacturers produced all airplane parts themselves, in the bygone era of vertically integrated industries. Nowadays Fokker is a subassembly link in the global company chain from material and part suppliers to airplane assemblers. Fokker has to compete with similar specialists. Integration has become an organizational, as well as a commercial and a logistic challenge.
Forming in practice

Working thermoplastic composites with continuous fibres requires an approach with which there was very little experience in the early years. Moulding and shaping thermoplastics is one thing, combining them with long strong fibres and subsequently forming them is yet another. You cannot just stuff fibres with polymer granulate into some moulding machine. Fibres require a certain treatment, which depends on their arrangement.

A woven structure sets limitations in formability different from the ones in structures, which are composed of UD tapes. Shaping this type of elements can save material and weight. In pressing structures made of UD-tapes it is understandably difficult to keep the fibre strands in good order. With the latest software, however, predicting wrinkles and delamination is possible. Nevertheless in everyday practice there is a striking similarity between pressing and folding thermoplastic composite sheet and the methods used for working sheet metal. It is not all that complicated for metal workers to learn how to make thermoplastic composite parts, which in the trade even carry the nickname “black sheet metal”. This is one good reason why fibre reinforced thermoplastics are doing so well.

In learning to understand composite technology they fill the gap between metal and thermosets. The most important rationale is of course that the thermoplastic plate principle ensures minimum material use and maximum understanding and control of structural quality of the combination of fibres and matrix to tailor structures to minimum weight functionality.

The right method to build lightweight structures from fibres and thermoplastics is a matter of exploration and discovery. Thinking in fibre arrangements, embedding fibres in a matrix and forming those into functional structures is radically different from putting metal parts together.

It is based on different principles, because the properties of the - at least two - participating materials bear a different relevance to structure than metals do. Metals have straightforward material properties, whereas composites are tailored material combinations. They are designed structures by themselves. The strength per unit weight of carbon fibre, for instance, may be a spectacularly high in comparison with steel, but this is meaningless without functional context.

On the other hand arranging and embedding fibres in a polymer allows much more precise tailoring of structures to fit functional requirements. There is less dependence on standard commercial material sizes. One can vary thickness and fibre orientation within a particular plate through intelligent lamination, in order to deal with stresses in exactly the right way, thereby saving mass: put fibres and matrix where you need them exclusively. So here we have the conceptual trade-off: design in thermoplastic composites is dependent on new (steadily evolving) application experience, but allows for considerable improvement in functional efficiency.

Designed for precision

The right method to build lightweight structures from fibres and thermoplastics is a matter of exploration and discovery. Thinking in fibre arrangements, embedding fibres in a matrix and forming those into functional structures is radically different from putting metal parts together.

It is based on different principles, because the properties of the - at least two - participating materials bear a different relevance to structure than metals do. Metals have straightforward material properties, whereas composites are tailored material combinations. They are designed structures by themselves. The strength per unit weight of carbon fibre, for instance, may be a spectacularly high in comparison with steel, but this is meaningless without functional context.

On the other hand arranging and embedding fibres in a polymer allows much more precise tailoring of structures to fit functional requirements. There is less dependence on standard commercial material sizes. One can vary thickness and fibre orientation within a particular plate through intelligent lamination, in order to deal with stresses in exactly the right way, thereby saving mass: put fibres and matrix where you need them exclusively. So here we have the conceptual trade-off: design in thermoplastic composites is dependent on new (steadily evolving) application experience, but allows for considerable improvement in functional efficiency.
Fibre control

Looking closer at composite structures it shows that engineering is still less similar to metal design than you may expect from the seemingly simple manufacturing methods. Structure definition starts on the small-scale level of fibres and polymers. At the time of birth of thermoplastic composites the main emphasis was on folding, inspired even by the refined Japanese art of origami. Sheet material is electrically heated locally (along a line) with a hot wire and subsequently bent. After that it did not take long to start developing ways of thermoforming textile reinforced polymer sheets to manufacture small stiffening parts, such as ribs, under high pressure in moulds. Up until this present day press forming (mechanically or with an autoclave) is Fokker’s main technology for part production. It is a quite interesting procedure since, apart from mouldability of the plastic matrix, it is determined by the kind of shapes fibre structures, such as textiles, draped fibre strands may allow. As described earlier this is where fibre reinforced thermoplastic plate is entirely different from metal: while metal is formed through plasticity, thermoplastic composites are drapable. Forming is different because of the fibres, and structural properties are different as well.
Welding composites

Thermoplastics melt when they are heated and, of course, because of this parts can be welded. There are several welding options, defined by the principle through which the interface material is heated.

The most common way is simply use an electrically heated soldering iron, but for plastics in serial production it is more appropriate to employ their insulating properties in ultrasonic welding, or friction welding, in which the interface heats up to melting temperature through moving the parts to be welded against each other. Stir welding is an in between principle, whereby both the parts that have to be bonded are heated through the stirring movement of a metal tool, while being pressed together.

Nice clean solutions are resistance welding and induction welding. In the former case metal wires in the interface are heated through electrical resistance. They melt the plastic surfaces surrounding them, because of which these merge. The wires simply remain in the weld. As a matter of fact they could theoretically be part of the woven or unidirectional fibre structure. Carbon conducts electricity. Therefore with carbon fibre reinforcement induction welding is an option: layers to be connected are gently clamped in a mould. A robot moves an electric coil along the seam to induce current. This causes the interface to become hot enough for the plastic parts to melt together.

When a new tradition begins, supposed advantages have yet to prove themselves. After a certain episode of learning they become clear and more refined. And then new unpredictable advantages reveal themselves, in function as well as in production. In rudders thermoplastic composite plate material can be uncommonly thin, so thin in fact, that there may occur some post-buckling during flights because of functional load. In thermoset composites this would not be condoned because of the danger of delamination after a certain period of use, whereas a thermoplastic structure can handle it.

In comparison with thermoset composites the main consequence of processing thermoplastics is more freedom in defining form and in the number of production steps. Apart from an increase in speed and simplicity (no clean room, no curing in an autoclave, short consolidation cycles), it is not necessary to produce entire parts in one go. They can be built step by step, laminating, heating and folding and welding, thereby allowing production of more complex lighter integral structures, with a better finish. Even a very simple rectangular sandwich panel gets nicely closed edges - edges and transitions generate most design challenges - by folding down one of the plates on all sides to cover the rather undefined honeycomb edge inside. For thermoset sandwiches this would have required gluing separate rims to all edges.
Test hierarchies

A question often asked concerning thermoplastic composites is: how do you test those materials for fatigue. The answer is simply that usually you don’t need to. The decrease in strength during load cycles is modest and scattered and there is no relatively steep decrease after a certain number of cycles, like you’ll find in aluminium. As a matter of fact thermoplastic composites are even less susceptible to fatigue than thermoset composites.

In general fatigue in composites concerns growth of delamination (fibres and matrix detaching and fraying), which is caused by impact. The same impact energy will cause less delamination in thermoplastic composites. Moreover, cracks in thermoplastic composites grow at a slower rate. Because of this thermoplastic composite airplane parts are not likely to fail because of fatigue, certainly in the range of loads they have to deal with. The structure follows a different concept. You don’t need to test clay for building a tent. Impact and delamination tend to determine vulnerability in composite structures and not fatigue. Delamination is the result of impact. It can be traced with the help of techniques that involve sound or with a method called “phased array inspection”.

Procedures for testing composite structures to minimize failure probability are defined along the lines of structural hierarchy. Often they are pictured as a pyramid, with the testing of constituent materials at the bottom. Actually, turning the pyramid upside down might be more logical, since part complexity increases considerably with the hierarchical level.

Fibres and matrix materials need to fulfil their material requirements. Next they are laminated. Plate properties in their turn depend on the combination of materials and fibre orientation. They are also determined in tests. Consequential stages all require testing methods that become more specific with part complexity. The final test of course concerns the complete structure.

The concept behind failure probability in thermoplastic composite structures is the same as in aluminium. Load and structural failure both have a normal distribution and the improbable combination of a very high load and early failure is resolved with a 1,5 safety factor. The difference with aluminium is that the same probability of failure requires less mass and can be achieved at lower costs.

Damage repair

Stage in classic structural repair procedure. The hole will be filled with a specially prepared aluminium panel.

During production and use of an aircraft and all its parts, things are bound to go wrong occasionally. Everything can happen in such a large and complicated product, from a small scratch on a floor tile to a costly mistake during a test just before delivery of a brand new aircraft. In comparison with the intensity of aircraft exploitation, damage does not really occur all that often. Still one has to be prepared, since grounding a plane is expensive.

Since damage doesn’t occur all that often, experience with repairing damaged thermoplastic composite parts is increasing slowly, but steadily. Restoring thermoplastic parts, in the same way that they were produced, usually is quite complicated if not impossible, because welding in difficult spots around corners between vulnerable surfaces is hardly an option. In this stage of development we have to resort to classic methods, accepting moderate conceptual compromises. Firstly there is a difference between cosmetic and structural repair. The first kind usually consists of closing a hole or a crack with fibres and a thermoset resin and consequently working the surface until it is flush. On the outer skin it can include metal mesh to deal with static electricity. The second kind of repair is gradually turning less complicated. Damaged sandwich structures are difficult to deal with in terms of reliable mechanical attachment.

Fokker reduces structural weight by producing monolithic discretely stiffened parts. Ribs and stringers then are amply available to attach new skin panels to with rivets or bolts. Aluminium repair tradition comes in handy. Nevertheless with the growth of the thermoplastics share in aircraft structures innovation of repair methods is emerging. Currently Fokker and NLR (Netherlands Aerospace Laboratory) are testing an “in field” repair principle, where the composite laminate is kept under vacuum while a heat source from one side provides welding conditions. It seems to work, but needs further investigation.
Continuous innovation

Fokker operates at the forefront of aircraft innovation. This is not a stroke of luck, but a crucial strategy for a supplier in global aircraft structure industry. In the continuous process of functional improvement, weight and cost reduction, and the evolution towards sustainable air transport, lagging behind simply is not an option. For thermoplastic composites this implies gradual implementation in everything from floor panels, wing parts and moveables in the past, to fuselage sections and all structural regions in the coming years. In a system of technology roadmaps, from the current state to the future, Fokker Aerostructures, proposes new concepts, selects the promising ones and develops the best into feasible product technology combinations. In the avantgarde of innovative sustainable development Fokker participates in networks of universities, customers, co-developers and suppliers in which skills and knowledge are shared and improved. Exploring the newest is both necessary and, admittedly, quite exciting.