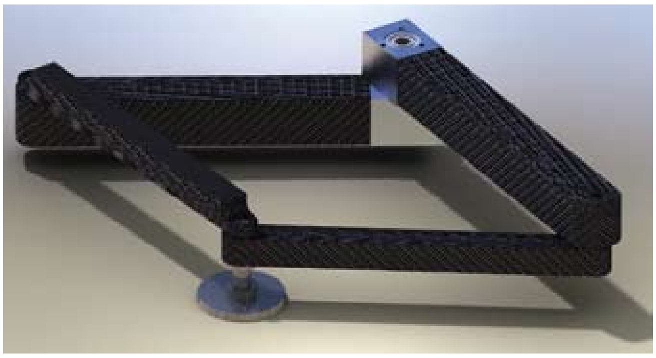
Rapid manufacturing composites for

Product development in the high-tech precision industry increasingly relies on the application of 'new' lightweight materials, such as carbon fibre composites. However, engineers lack composite know-how and experience. Last year, the Mechatronics department at Fontys University of Applied Sciences started the project 'Composites in Mechatronics', aimed at developing knowledge about carbon fibre composite machine parts, investigating production cost reduction and improving knowledge transfer to SMEs.



• *Henk Kiela, Bart Bastings and Tim de Hond* •

The most commonly used materials in mechanical precision engineering are steel and aluminium. Engineers are familiar with the properties of these materials and can develop complex structures. But because of the end-users' demands, the physical limits of steel and aluminium in today's precision products will be reached soon. It is essential for the high-tech precision industry to develop new products, using 'new', lightweight materials, such as carbon fibre composites. However, using composites will demand a different way of working for the precision engineers, since composites are inhomogeneous and anisotropic materials, whereas steel and aluminium are homogeneous and isotropic materials. Currently, engineers lack know-how of and experience with composites.

Carbon fibre is not a new product and is widely used in the automotive, aerospace and defence industries. Composite manufacturers are confident in producing products for these industries. Products for high-end machinery require a different approach with which composite manufacturers are not familiar. Their mindset is focused on material strength and low weight, whereas the focus in high-end machines is on stiffness and low weight.
For mechanical engineers, carbon fibre machine parts can be of great value, as they allow the realisation of higher accuracy in high-dynamic machinery. This can be attributed to the damping properties (to a large extent an unknown factor) and the low specific weight of carbon fibre composite materials, resulting in high natural frequencies. Another advantage of carbon fibres is the opportunity of creating a variety of differently shaped products.

RAAK project

Since September 2009, the Mechatronics department at Fontys has been working actively on 'Composites in Mechatronics' in a so-called 'RAAK' project (Regional Attention and Action for Knowledge circulation). RAAK is

and lightweight more precision

aimed at knowledge exchange in regional innovation programmes between universities and small and medium-sized enterprises (SMEs). The consortium set up for this project consists of Fontys' Mechatronics department, the INHolland Composites Lab in Delft, the association for the synthetic composites industry in the Netherlands (VKCN/NRK), Q-Sys, and DSPE. The consortium partners and regional SMEs (engineering, manufacturing and end-users) are collaborating to investigate the potential of carbon fibre composites for use in high-tech systems.

The main focus of the project is developing knowledge about carbon fibre composite machine parts. All available knowledge is shared with the partners. The Fontys Mechatronics department is researching what know-how is missing. This has resulted in the development of a test bench on which the material properties of different carbon fibre products can be measured. The products are dynamically actuated on torsion, bending, and push/pull forces, after which the effects of product behaviour are measured. Another project result is the realisation of a manual for composite design in the Finite-Element Method (FEM) software ANSYS©.

Air-hockey Robot

To test the theory, a pilot project was defined in close cooperation with TMC Mechatronics, one of the project partners, and with support from the industrial participants. TMC Mechatronics was working on an air-hockey playing robot. This Air-hockey Robot is intended to serve as an eye-catcher for TMC at conventions and events; see Figure 1.

The engineers at TMC Mechatronics developed this robot with four aluminium arms. The two arms closest to the puck had a square profile with the dimensions 400 mm x 40 mm x 1.5 mm. The other two arms, closest to the electric motor, had a square profile of 400 mm x 60 mm x 1.5 mm. All four arms together had a total weight of 4.92 kg, including the motor interface. The first bending mode of the arms in push direction determines the speed and accuracy of the total system. For the aluminium arms, this frequency is 84 Hz.

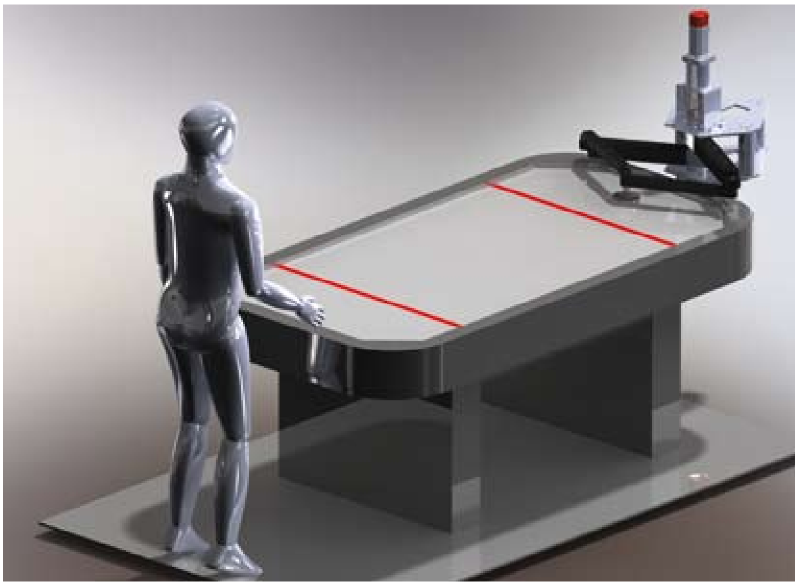


Figure 1. Air-hockey Robot impression.

Mechatronics at Fontys

The authors work for the Mechatronics department in the College of Engineering at Fontys University of Applied Sciences in Eindhoven, the Netherlands. Lector Henk Kiela is head of the department; Bart Bastings and Tim de Hond are researchers. The Mechatronics department conducts applied research in various fields of robotics and high-tech mechatronics, in close cooperation with industry, universities and education.
Know-how about mechatronics, robotics, vision, applied physics, computer technology, mechanical and electrical engineering is put into practice in various projects, such as Low Cost Motion Control, Remote Robotics, and Composites in Mechatronics. Students get involved through internships or graduate projects. In most cases, knowledge and experience is translated into educational material used in the Fontys mechatronics and (in general) engineering curricula.

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TMC offered to use their Air-hockey Robot as a demonstrator in the project. The objective was to increase the robot's performance by replacing the aluminium arms with carbon fibre arms. The goal was to reduce the mass inertia and increase the first bending mode from 84 Hz to at least 200 Hz.

Four students made a complete redesign of the arms and calculated the enhanced performance. During the engineering phase of the arms, the students tried to find an optimum between low weight, high bending stiffness, high torsion stiffness and low production costs.

To achieve this inertia reduction and increase the natural bending mode frequency, first the required stiffness of the arms was calculated. To do this, a model of the robot was made in which the assumptions were that the large arm near the robot has to be stiff in bending direction. The small arms near the pusher were assumed to be rigid in push/pull direction. This resulted in a simple model of one arm and a mass, see Figure 2, with bending stiffness *k* (unknown) and mass *m* (1 kg). The mass was calculated from the mass of one aluminium arm, pusher and all connecting parts, such as bearings.

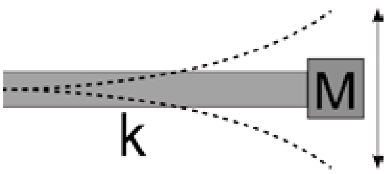

Figure 2. Simple cantilever beam model.

Now the required stiffness of the arm could be calculated with the standard equation for a mass-spring system:

$$f_e = \frac{1}{2\pi}\sqrt{k/m}$$

and thus:

$$k = \frac{f_e^2 \cdot m}{(1/2\pi)^2}$$

which results in a required stiffness of $1.6 \cdot 10^6$ N/m for a frequency of 200 Hz.

For a beam clamped on one side and loaded at the tip, a well-known equation is often used to calculate the deflection for a given load, and thus the stiffness:

$$k = \frac{3EI}{l^3}$$

or when shear deformation is also accounted for:

$$dx = \frac{Fl^3}{3EI} + \alpha\frac{FL}{GA}$$

where α is a geometric constant and *G* is the shear modulus.

This works very well for most (slender) beams made of steel or aluminium. But for carbon fibre the formula does not give usable results, because of the orthotropic behaviour of this material. When a carbon fibre laminate is used to make a square tube, the *E* and *G* moduli *in plane* are different from the *E* and *G* moduli *out of the plane*; see Figure 3.

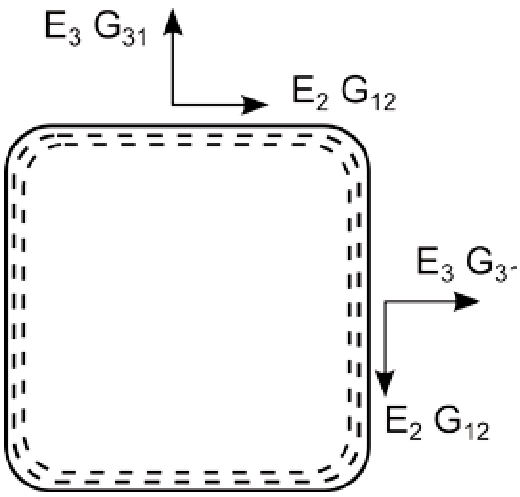

Figure 3. Orthotropic properties of a composite beam.

For this reason, these calculations were only used as a global indication; the final design was based on a FEM model of the composite beam. In this model the total laminate of the beam was modelled as a stack of individual layers with orthotropic properties; see Figure 4. With this set-up it is very easy to change the lay-up of the carbon fibre lamellas and investigate the effect on stiffness for different lay-ups.

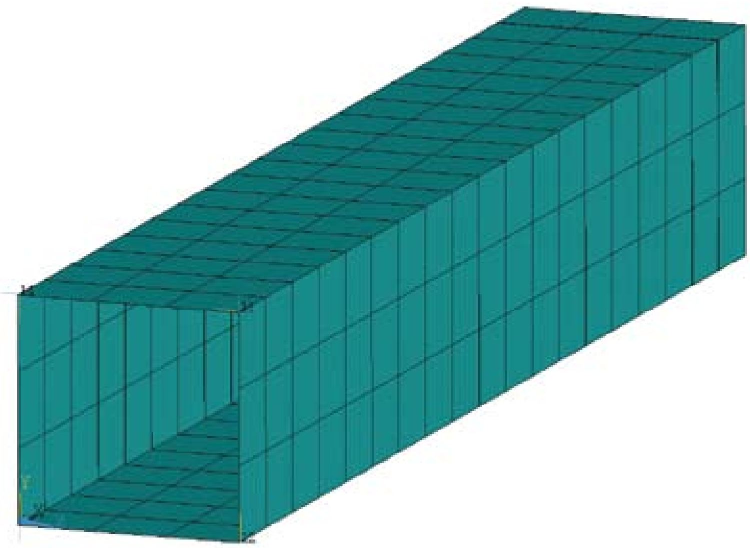

Figure 4. Model set-up, with the sides of the beam modelled as thin shells.

After a few iterations, a lay-up was chosen that resulted in a bending stiffness of $1.6 \cdot 10^6$ N/m (which was the required value) as well as good torsional stiffness. This lay-up consists of one layer with ± 45° fibres on the outside, seven layers of UD fibres in the middle and three layers of ± 45° fibres on the inside; see Figure 5, and see the box on the right for an explanation of composite terminology.

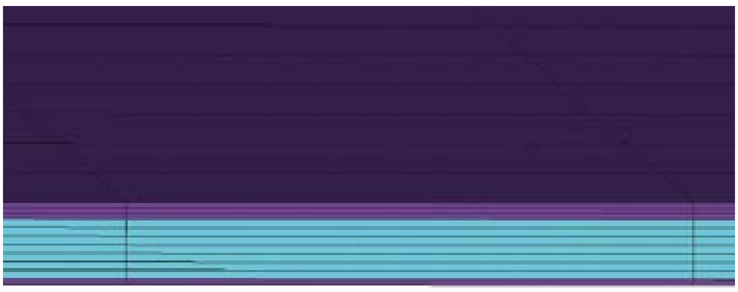

Figure 5. Different layers (the ± 45° fibres in purple, UD fibres in blue) in shell elements.

Composite production

Carbon fibre products are also called carbon fibre reinforced plastics, because that is exactly what they are. A resin, usually epoxy, is used as a matrix material in which the fibres are embedded. The fibres provide the stiffness and strength (the reinforcement), and the resin is used to keep the fibres together.

A frequently used method to put the resin and fibres together is 'Resin Transfer Moulding', were dry fibres are placed in a mould and the resin is sucked in between the fibres through a vacuum in the mould. Another method is when a manufacturer uses pre-pregs, which is an intermediate product of fibres that are pre-impregnated with resin. These pre-pregs are stacked and placed in a mould. A vacuum bag is put over the mould and the entire set-up is placed into an oven or autoclave, where the resin can cure under pressure and heat.

The most important considerations when designing with carbon fibres are the fibre type and lay-up of the fibres. Because the fibres are only stiff in their longitudinal direction, they must be stacked on top of each other at different angles to get stiffness and strength in all directions needed. Such a stack is called a laminate. This means that a designer can tailor the mechanical properties of the laminate to meet his needs.

When the fibres are all in the same direction, this is called UD (unidirectional). A UD lay-up gives a very stiff laminate in one direction (high E-modulus), but is very compliant in all other directions. This is useful when only pure push-pull forces are to be expected. When shearing is important, a ± 45° lay-up is used, because this will result in a very high G-modulus in the shearing direction. Most of the time a combination between these two is used to get the right mechanical properties.

The advantages of carbon fibre over traditional materials such as aluminium and steel are that it has a low weight and that the mechanical properties can be tailored to the designer's needs, but this comes at the cost of more engineering effort to calculate the expected stiffness and strength of a carbon fibre laminate.

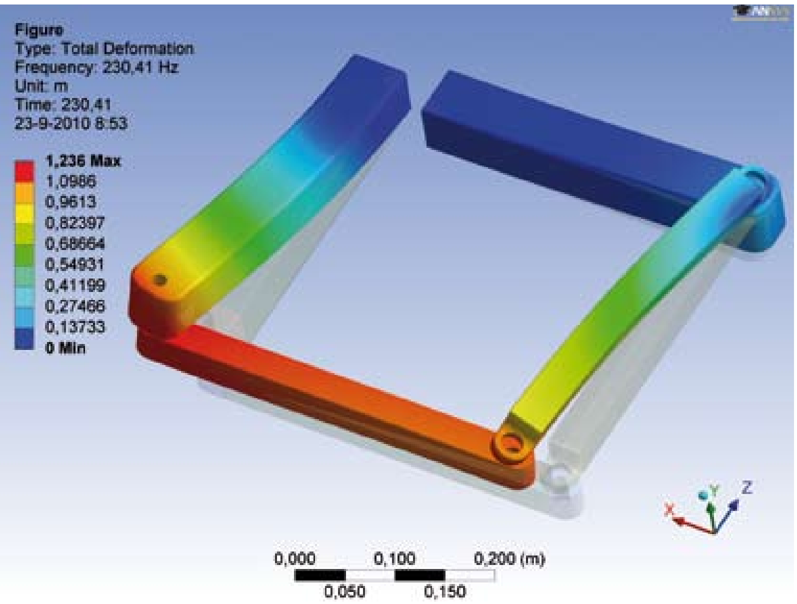

Figure 6. Modal analysis of composite air-hockey robot arms.

These calculations were done for all arms, and finally a model of the entire set-up was made. In this set-up, all degrees of freedom of the model and also the different layer properties were taken into account. A modal analysis was conducted and the first bending mode was calculated to be 230 Hz; see Figure 6.

In the final design, see Figure 7, the weight of the arms changed from 4.92 to 4.66 kg. It has to be noted that most of this mass is closest to the electric motor that drives the arms. This motor does not feel mass but mass moment of inertia. The mass moment of inertia for the aluminium arms was 0.60 kgm^2. The moment of inertia for the carbon arms is 0.23 kgm^2, a reduction of 62%. As mentioned earlier, the first bending mode is very important because it determines the speed and accuracy of the system. This mode increased from 84 Hz to 230 Hz. In theory, the system with carbon fibre arms should perform more rapidly and more accurately, which makes the Air-hockey Robot even more difficult to beat.

Rapid manufacturing

Another goal of the ‘Composites in Mechatronics’ project is to investigate the possibilities to reduce production costs of carbon fibre products. Carbon fibre parts are classically produced using popular methods such as lay-up on a model or pressing and curing of pre-pregs material in a mould. The model or the mould is generally designed and produced separately, before actual production of one or more carbon fibre parts can be started. For the new application field investigated in this project – the use of carbon fibre machine parts – the production quantities for such parts are generally between 1 and 100. Both the initial

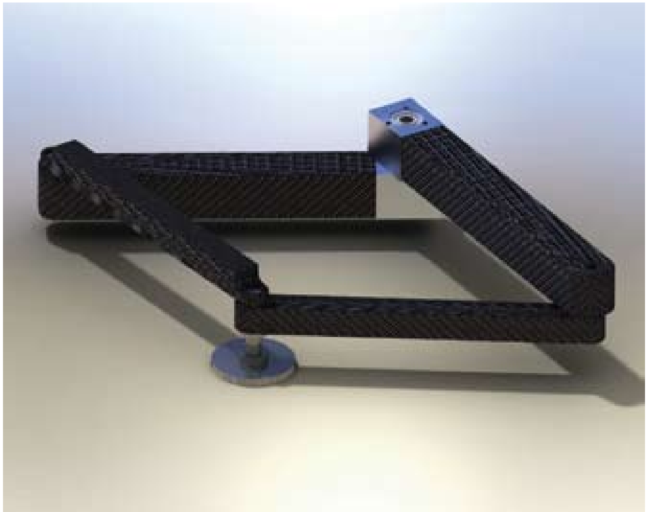

Figure 7. The final design of the air-hockey robot arms.

cost and the lead time before getting the first part can be a problem when using the classic manufacturing methods.

The idea arose to experiment with rapid manufacturing techniques in the process to produce the models or moulds. Rapid manufacturing (RM) has become a mature way of producing plastic parts, not only for commercial applications, but also for part manufacturing purposes. The capabilities of these RM parts are, in general, underestimated. But there are a few interesting features that favour the use of RM for the model or mould, being the design flexibility and the fact that the cost for a complex shape is not different from a simple shape. Other advantages are the short lead time of a few hours between CAD design and the actual part coming out of the RM equipment, and the minimal waste.

Parts can be produced by RM in various plastics and in metal as well if needed to produce stronger parts. With the current technology in RM, metal parts are still quite expensive. Therefore, the choice was made in this project to explore the capabilities of producing a polycarbonate (PC) mould for a complex shape. This experiment was conducted in close cooperation with project partner Airborne Composites. Based on their advice, the mould was split into two halves. Figure 8 shows the resulting mould. The total cost of the PC mould was around € 500, including the man hours to design the mould in CAD.

Then, the carbon part was formed in the mould, using a standard vacuum bag, fabrics and tooling resin that cures at 80°C. Because a vacuum bag, not a pressure bag, was used, a simple mould could be used that did not have to withstand high pressure. The product was cured in a standard oven at a temperature not exceeding 100 °C. The PC has a heat deflection temperature of 138 °C at 66 psi

Figure 8. The polycarbonate mould produced with RM, for manufacturing complex-shaped composite products.

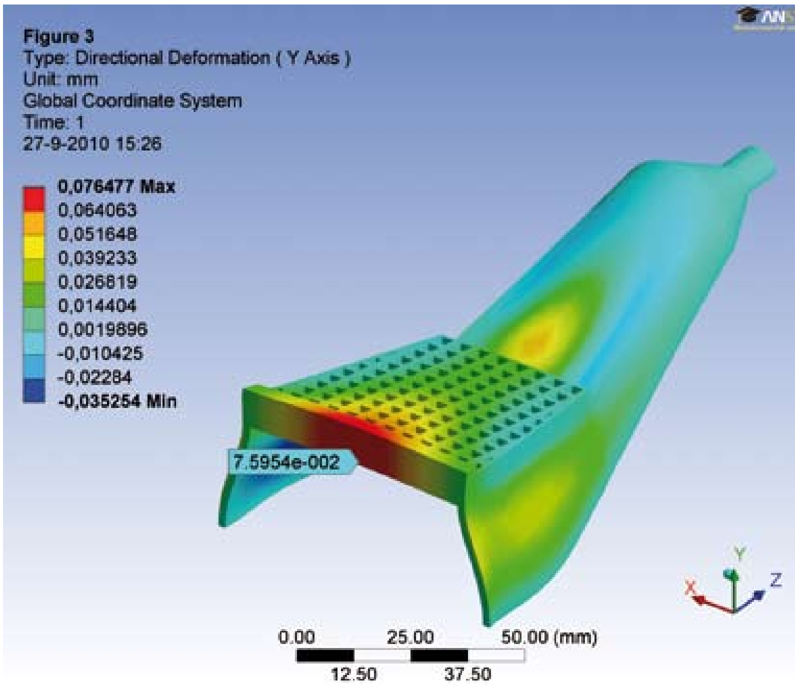

Figure 9. Study of the deformation of the mould due to internal pressure.

(4.6 bar), and 127 °C at 264 psi (18 bar). Due to its amorphous nature, PC does not display a melting point. Airborne produced the carbon part in the mould and simply removed the formed part from the split mould without damaging the mould parts.

Additionally, a FEM study was performed to investigate the possibility of using an RM mould in combination with a pressure bag. This means that the mould has to withstand an internal pressure, otherwise the final product will not meet its dimensional specifications; see Figure 9. An internal overpressure of 1 bar turned out to cause a deformation of the mould of less than 0.1 mm. However, it was decided to use a vacuum bag.

Conclusions

Using RM moulds or models opens up a new way of designing and manufacturing products in small numbers, as it combines low-cost moulds having complex geometries with short lead times. Further work will be done to investigate and compare the cost and lead times of classically produced moulds and RM moulds.

It is obvious that a plastic mould has some limitations. The stiffness of plastic is significantly less than that of metal. This can be partially compensated by using (more) ribs in the mould to support the thin-walled scale forming the parts. Mould behaviour can be optimised for the part manufacturing process by means of the proper use of FEM tools. Thermal limitations are another potential hindrance to the use of RM moulds. It is known that at room temperature, carbon fibre parts only gain 80% of the strength and density they would get in an autoclave. But many machine parts are not designed and optimised for strength. The major design criteria are weight, stiffness and damping (dynamic behaviour). Of these three properties, damping will be favourable for a part cured at room temperature. The fibre volume ratio (the percentage of the total volume that is constituted by fibres) and stiffness will be better when a part is cured in an autoclave. But how much variation in properties can be found, will be part of further research in this project.

By taking into account these design aspects in the manufacturing of high-graded carbon fibre machine parts with the use of RM moulds or models, an important step was made toward low-cost manufacturing with short lead times. Other expected advantages will be explored later in this project, such as fixing metal or plastic attachments for bearings and support functions in the same process step as forming the carbon part in the RM mould. The mould can be modified such that the attached part is fixed to the mould to achieve better accuracies for the completed assembly. This could make post-processing, for example milling of bearing holes, redundant or at least save costs.

Acknowledgement

The authors would like to thank ‘Peters freeswerk en modellenbouw’ for manufacturing the moulds for the air-hockey robot arms, and Refitech for making the carbon fiber air-hockey robot arms using these moulds.