Summary

In order to reduce the environmental impact of the manufacture of products for the aircraft industry, it is necessary to reduce inputs (raw materials, energy, water, etc.), outputs and nuisances (waste, effluents, etc.) throughout the life cycle. The manufacturing technology currently used for helicopter doors is to place pre-impregnated sheets of carbon-fibre reinforced thermoset (prepregs) in the required fibre direction by hand. The subsequent curing of the carbon-fibre reinforced thermosets is performed in an autoclave. The highly energy-intensive autoclave cycles as well as the noxious effects due to processing thermosets require more ecological friendly solutions. If this procedure is replaced by laser-assisted Thermoplastic Fibre placement (TFP) with a thermoforming step in between, it would be possible to abandon the time- and energy-consuming autoclave process. The use of thermoplastics increase the potential for recyclability, which can be exploited in favour of a reduced environmental impact. The principal benefit of TFP is the possibility of in-situ consolidation, eliminating the need for bonding, riveting, bolting or other joining technologie . In addition, without the use of an autoclave faster cycle times can be achieved.

The project DEfcodoor comprises of the "**D**evelopment of an **e**co-friendly **f**inal **co**nsolidation step using thermoplastic fibre placement for a helicopter **door**" and is part of the Green Rotorcraft 6 (GRC) programme of the EU research project Clean Sky. The laser-assisted TFP and thermoforming processes are combined to produce structures consisting of stiffener and skin for helicopter applications. Customised laminates with local reinforcements for example are manufactured by laser-assisted TFP and are then thermoformed into hat profiles. After insertion of a pre-cast core a skin laminate is joined in-situ to the thermoformed stiffener by TFP. The solulable core is removed and an in-situ joined part is obtained. The manufacturing steps of DEfcodoor are shown in Figure 1.

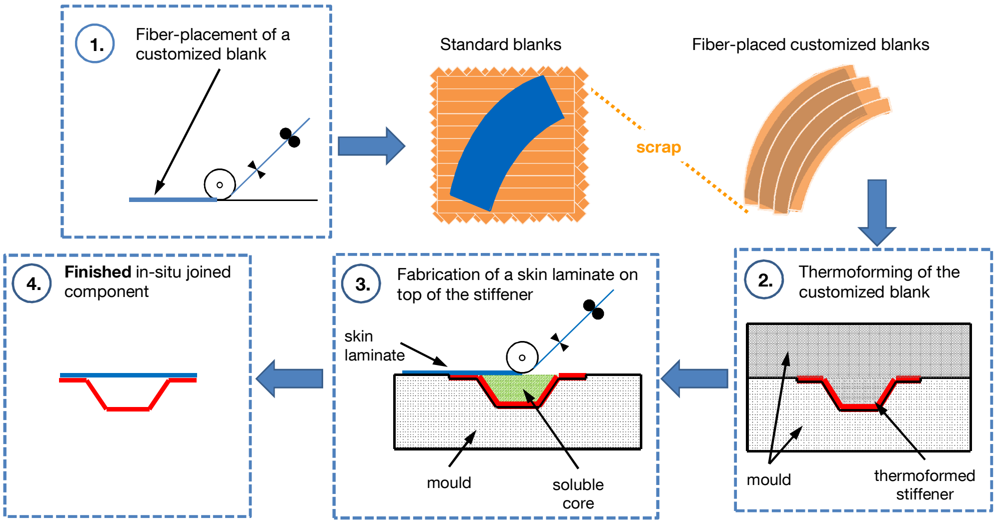

Figure 1 Single manufacturing steps within the DEfcodoor technology

A thermoplastic matrix material suitable for aircraft applications had to be selected. Therefore, a trade-off between performance, availability and costs was made. Polyethersulfone (PES) was selected; an amorphous high-performance thermoplastics. The chosen thermoplastic material is commonly reinforced by AS4 fibres and is available in the form of unidirectionally pre-impregnated tapes. Carbon-fibres were selected due to their high strength and modulus in general.

To identify the relevant process parameters of the laser-assisted TFP technology with significant effect on the laminate quality, various testing methods were investigated. A modified T-peel test was chosen to find an optimum setting for the dominant process parameters in an efficient manner with respect to manufacturability and testing. The experimental setup of T-peel tests is presented in Figure 2.

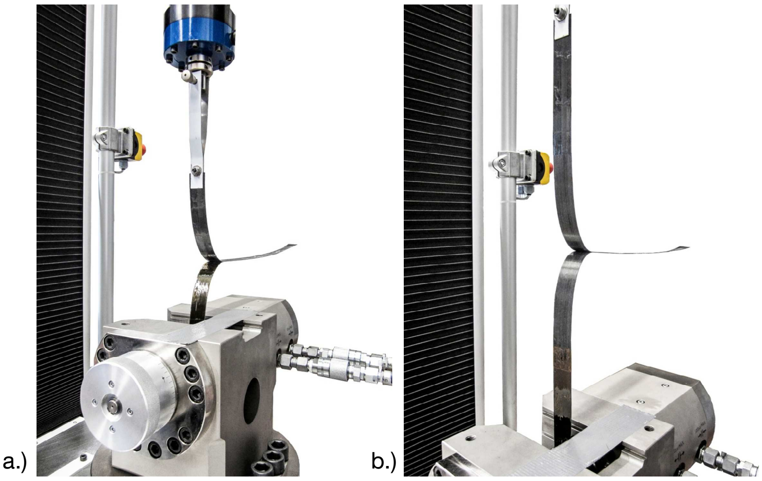

Figure 2 T-peel test of thermoplastic UD prepreg; a) Initial state of specimen and b) Specimen during testing

The process parameters to be varied were the placement speed of the TFP head, the nip point temperature at the focal spot, the tool temperature of the heating plate, the tape tension and the consolidation force of the consolidation roller. After conducting several process parameter variations, tape tension and the consolidation force were found to have low influence on the laminate quality but are important parameters with respect to tape placement accuracy. With PES being an amorphous thermoplastic the tool temperature has no significant effect on the mechanical performance of the laminate. However, heated tooling decreases residual stresses that are conditioned by different coefficients of thermal expansion of carbon fibres and PES. Placement speed and nip point temperature had significant effects on the mechanical performance of the specimens. Sufficient energy was required to decrease the viscosity of the thermoplastic properly so that possible intralaminar and interlaminar voids can be penetrated by matrix material. The more time is available during laser-assisted TFP the higher the degree of bonding becomes. As soon as full contact was achieved between two placed tapes, diffusion of molecular chains across the interface can take place and strengthen the bond. Here, time and temperature are most influential factors. Besides the dominating process parameters the quality of the tape material had a significant impact on the laminate quality. Most of the employed tape spools showed non-uniform fibre-matrix distribution along tape width and thickness. As a consequence, dry spots with high agglomeration of fibres and resin-rich areas were detected. The non-uniform distribution of fibres and matrix within the tapes also resulted in a distortion of the tapes which affected the tape placement accuracy and handling.

The process parameter optimisation was conducted by varying one process parameter while keeping the remaining parameters constant. The evaluation of the T-peel test results was conducted in combination with microscopy and led to an optimum process setting which was then used for material characterisation of AS4/PES tapes. A standard testing program including tensile, compressive and shear properties was conducted to evaluate the performance of the chosen material. To classify the laminate quality upon processing with the laser-assisted TFP technology a comparison to post-consolidated specimens was made. The latter were manufactured with laser-assisted TFP first and then post-consolidated in an autoclave or press. In-plane shear tests were used to compare in-situ consolidated to post-consolidated specimens as primarily matrix-dominated and matrix/interface related properties are affected by post-consolidation. The test results exhibited an increase in longitudinal shear strength for the post-consolidated specimens by approximately 20%. The reason for improved mechanical properties was found to be in a decreased thickness of post-consolidated specimens which is achieved due to higher pressures applied during autoclaving or press forming. A higher consolidation pressure enables the removal of air within tapes and between plies. The properties of in-situ consolidated specimens are expected to improve when tapes with high quality and low void content are processed. The low consolidation pressure during laser-assisted TFP is not sufficient to remove entrapped air within the tape material.

To obtain material properties on a subcomponent level, a demonstrator part (subcomponent) was designed and a test strategy developed. The subcomponent revealed a symmetrical cross-sectional area to avoid any influences due to asymmetries during mechanical testing. The test strategy comprised non-destructive inspection of laminates before and after thermoforming, mechanical testing of the finally in-situ joined subcomponent with a four-point bend test and examination by microscopy. Therefore, laminates were manufactured with laser-assisted TFP to thermoform them into symmetrical hat profiles to be the stiffener of the subcomponent. The quality of the laminates was examined with visual inspection and with dimensional inspection. A manufacturing concept for the core material was developed to ensure high dimensional accuracy. The core material used was Aquapour®, selected due to its high compressive strength as the core material needs to withstand the consolidation pressure during fibre placement. In addition, Aquapour® has a low environmental impact and is soluble in water. The fibre-placed laminates were successfully thermoformed into stiffeners as part of the subcomponent. The dimensional inspection of the stiffener showed that there was a decrease in thickness due to high pressures during thermoforming in comparison to fibre-placed laminates. Additionally, distortions of the stiffener due to residual stresses were not detected. Non-destructive inspection by ultrasound scanning was conducted and showed no major irregularities in the thermoformed laminate.

As preparation for the in-situ joining of skin layers to the thermoformed stiffener, a tooling concept was designed and implemented as described in Figure 3.

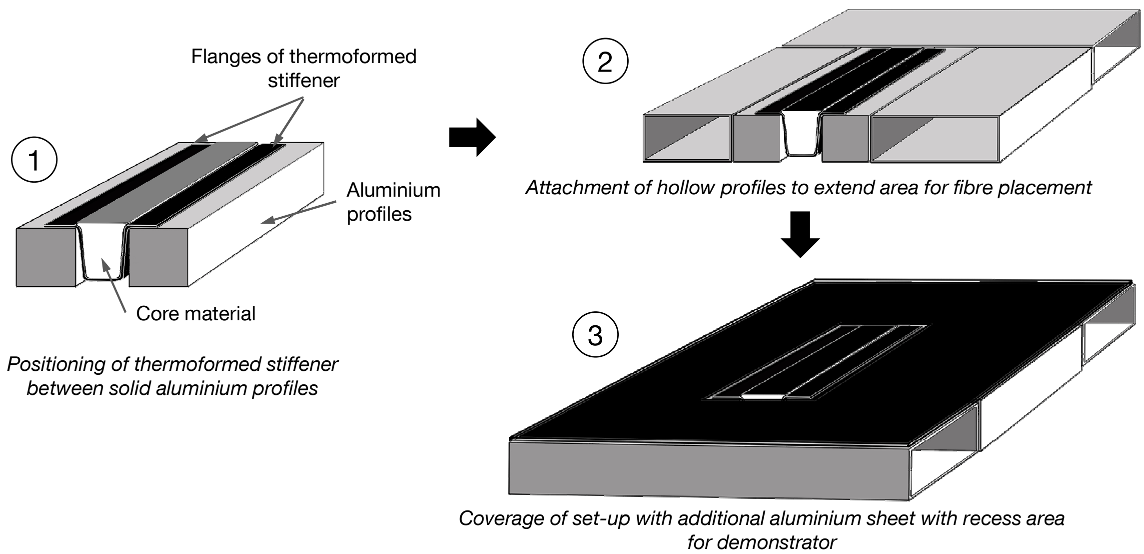

Figure 3 Manufacturing concept for in-situ joining of demonstrators

The concept consisted of an arrangement of aluminium profiles which enabled the positioning of the thermoformed stiffener to be varied. The setup was covered with an aluminium sheet with a recess area for the thermoformed stiffener. In-situ joining of skin layers to the thermoformed stiffener required different process conditions than the manufacture of laminates with laser-assisted TFP. Typically, the desired nip point temperature is set and the laser power is controlled by contactless temperature measurement. The control of the laser power enabled adaption to variable tape quality and maintained the desired temperature. During in-situ joining, the TFP head passes different substrate materials such as aluminium, thermoformed AS4/PES and core material during in-situ joining. The resolution of the controller for the laser regulation was insufficient to maintain the correct nip point temperature at the thermoformed flanges. As a result, in-situ joining to the thermoformed stiffener was not achieved with regulated laser power, hence the laser power was set to constant values. This required the development of a further testing method to find the optimum parameter set to join skin layers to the thermoformed stiffener. The test setup was derived from the tooling concept for the in-situ joining to create process conditions close to reality. Test specimens were manufactured for short beam shear tests. The varied process parameters were laser power, tool temperature and angle of the laser optics. Latter is an important parameter with respect to adjusting the heat distribution to substrate and incoming tape and was previously set automatically by the laser power control. The evaluation of the process parameters resulted in an optimum parameter set which was employed on the thermoformed stiffener of the subcomponent. Since the thermoformed flanges of the stiffener were twice as thick as the short beam shear test specimens, they extracted more energy and required a further increase of the laser power. Skin layers were successfully joined to several thermoformed stiffeners by using one tape spool only. When the empty spool was replaced with a new one, the process settings did not lead to continued success with joining. Process- and material-related reasons were investigated to find the reason for the poor joining. The highly variable tape quality was found to be the reason that reproducible in-situ joining process was not possible. Applying constant process settings is not possible with high variability in the tape quality. Hence, process parameters would need to be changed for each spool. It is assumed that the in-situ joining process works well when tapes with constant quality can be supplied and when the response time of controller at the TFP head is increased.

As the successfully in-situ joined stiffeners were investigated under the microscope and more stiffeners could not be joined successfully, mechanical testing of the demonstrators could not be conducted. However, three-point bending tests were conducted to compare thermoformed specimens to in-situ consolidated specimens. Specimens were cut from the crown and the flanges of a thermoformed stiffener to investigate the effect of thermoforming on the laminate quality. Similarly to post-consolidated specimens the flexural strength of the thermoformed specimens was increased by 21% compared to in-situ consolidated specimens.

The subcomponent consisted of 2D laminates manufactured with laser-assisted TFP that were thermoformed to symmetrical hat profiles. The last demonstrator within DEfcodoor, the feasibility article, revealed a complex unsymmetrical cross-sectional area and double-curvature. The design of the feasibility article was based on the current helicopter door of EC 135. Since thermoforming of UD laminates into complex double-curved structures is highly challenging, a concept with optimized fibre orientation was developed to be manufactured with laser-assisted TFP. 0° plies of the layup were steered along the curvature of the feasibility article as can be seen in Figure 4.

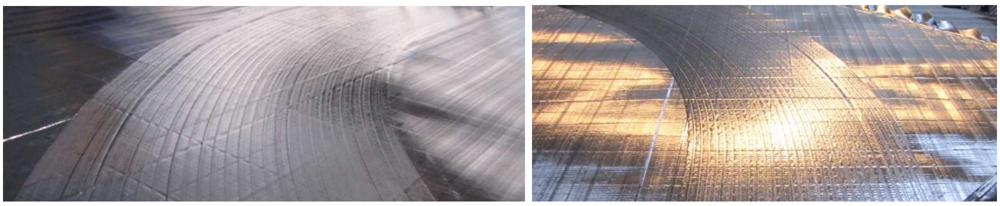

Figure 4 Steering of 0° plies along the curvature of the feasibility article during TFP

Standard laminates without fibre steering were manufactured to compare them after thermoforming. The results from thermoforming both laminate types were examined visually and under the microscope as shown in Figure 5.

Figure 5 **Feasibility article stiffeners upon thermoforming laminates with steered 0° plies and standard blank (below)**

A slight increase in number of wrinkles was detected for the standard laminate. Under the microscope strong deviations from the original lay-up were observed for the standard blanks. Micrographs of laminates with fibre steering showed that the fibre orientation of the 0° plies was maintained along the curvature of the feasibility article. Steering of 0° plies had a positive effect on fibre orientation. However, the positioning of the laminate in the mould during thermoforming was found to be a highly influential factor on the laminate quality.