Manufacture of nominal-shape composite stiffeners using autoclave injection

Composites are the material of choice for today's aircraft structures due to their excellent weight-specific performance. Recent dry-fibre technology developments open the door for infusion-based composites to become a serious competitor for the widely adopted prepreg-based structures, which currently dominate aerospace structural applications.




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Composites manufactured through an autoclave injection process have the potential to compete with prepreg structures without the performance or weight penalties observed in the past. Composite manufacturing companies are facing demanding challenges. On the one hand, they strive for significant cost reductions in high-performance composite manufacturing. On the other hand side, they need to fulfil strict tolerance requirements in order to avoid assembly bottlenecks due to a lack of dimensional fidelity. Therefore, they demand the capability to derive compensated tool geometries at the lowest possible cost, preferably without extensive prototype manufacturing. Due to the high cost pressure in the market, methodologies are desired that require as little effort as possible to derive reliable compensation measures allowing the fabrication of parts within narrow tolerances.

Embraer, Toho Tenax and DLR took up these challenges in a recent project. They developed an autoclave injection manufacturing process for a ∠ -stiffener geometry shown in Figure 1. The composite stiffener is composed of Toho Tenax's latest generation textile material Tenax® Dry Reinforcements using Tenax®-E HTS45 E23 12K carbon fibre in a non-crimp fabric and an aerospace epoxy resin. The part's lay-up, the geometry and the corresponding geometrical tolerances were provided by Embraer. The Institute of Composite Structures and Adaptive Systems (FA) of the German Aerospace Center (DLR) was in charge of the tool design and the manufacturing concept. The stiffener's dimensions and a schematic of the aluminium tool concept used are shown in Figure 1.

Autoclave injection process for high-performance composites

Autoclave injection-based composite manufacturing combines the advantageous aspects of conventional autoclave manufacturing and dry-fibre-based infusion techniques [1]. In particular, the control of the injection pressure p_{resin} and autoclave pressure $p_{autoclave}$ allows for adjusting the laminate thickness, the void content and the fibre-volume fraction. A novel process control technology based on ultrasonics can support this process beneficially as it makes it possible to supervise the flow front propagation and in-situ part thickness

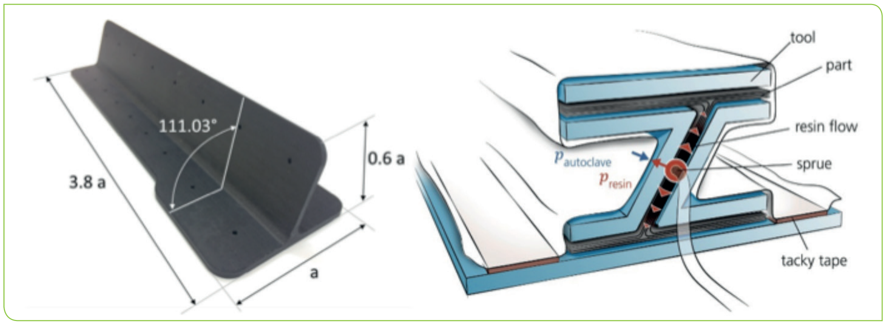

Fig. 1: Composite stiffener dimensions (left) and the aluminium tool concept used (right)

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measurement [1, 5]. This data can serve as input for controlling the differential pressure $\Delta p = p_{autoclave} - P_{resin}$ by adjusting the resin pressure, for example. The developed manufacturing process is a single-line injection (SLI) process with a cure temperature of 180°C and an autoclave pressure of 0.6 MPa, which was successfully used for composite ribs [1] earlier.

Dry-fibre technologies make it possible to use draping for more complex part geometries that cannot be produced using conventional prepreg-specific manufacturing technologies such as automated tape laying (ATL) and automated fibre placement (AFP). The Tenax® Dry Reinforcements HTS45 dry-fibre material, applied for the ∠-stiffeners, has a multi-material architecture made up of a +45° composite ply, an interleave toughener, a -45° composite ply, another interleave toughener followed by a powder binder surface layer. It has an areal weight of approximately 400 g/m². The laminate stacks used for the stiffeners are preformed in a vacuum-based preforming step, utilizing a membrane technique. Aerospace gusset fillers (noodles) are used at the junction areas of the C-profiles and covers. This is important in order to avoid neat resin agglomeration in the filler area, which is critical from a stress point of view. Moreover, neat resin areas often lead to cracks mainly induced by the considerable resin cure shrinkage.

Adequate resin flow control is mandatory when manufacturing aerospace-quality parts using an injection process.

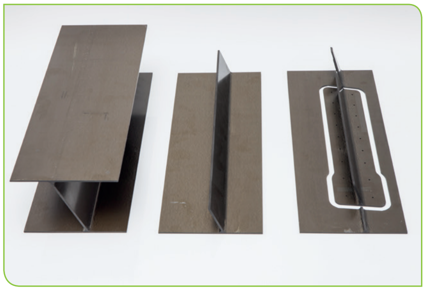

Fig. 2: Manufactured CFRP component, segmented frame and final component developed by Embraer, Toho Tenax and DLR

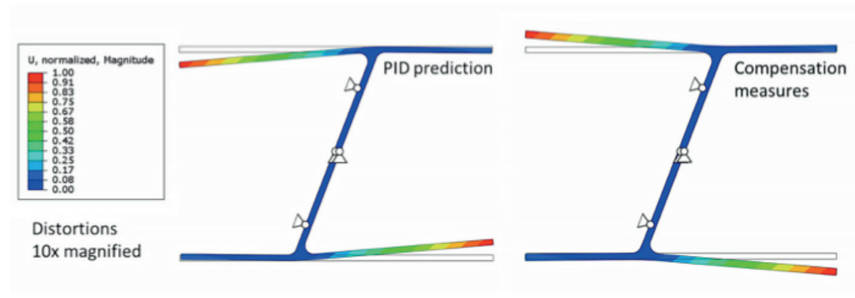

Fig. 3: Normalized PID predictions and compensation measures derived through the P-approach

Therefore, simulation techniques are applied to assess resin flow and to define robust injection strategies. For the structure at hand, the injection concept was designed using RTM-Worx simulations and in-house experience. Figure 2 gives an overview of the fabrication steps, showing the manufactured composite structure on the left, the trimmed interstage product in the middle and the final part on the right.

Straightforward prediction-based tool compensation

Process-induced distortions (PID) occur inevitably when manufacturing composite structures [3]. Distortions arise from the material's anisotropy. Reliable compensation strategies are essential in order to fabricate nominal-shape parts. As the compensation task often pops up when the part design and stress analyses are finalized, it represents an additional work step within the tool design process. Therefore, methods with an excellent trade-off between prediction effort and prediction accuracy are particularly demanded by composite manufacturers. For the stiffener profile at hand, the so called P-approach was applied [2, 4]. This approach pursues a semi-numerical strategy that focuses on predicting process-induced distortions of composite structures. In contrast to state-of-the-art physically-based process simulation approaches, which demand costly material parameter characterization of fibres and resin as well as complex numerical modelling, the P-approach utilizes conventional engineering constants and a single additional parameter capturing distortion. This dimensionless parameter is derived from the distortion of a manufactured reference specimen by an analytical transfer. Even available data from the literature or previous experience can be used for a good qualitative estimation. The P-approach can be applied to conventional solid and shell elements [4]. In the present case of the ∠-stiffener, an efficient 2D cross-sectional model was used, as the part's cross-section does not change along the part length. The manufactured cross-section is a junction of two C-profiles covered with two flat laminates on either side. These covers affect the overall distortion mode, which makes a simple experience-based estimation of process-induced distortions impossible. Therefore, the application of the P-approach was mandatory to derive the intended compensation measures. As the web is not perpendicular to the chords, asymmetric compensation measures are derived for both the long and the short legs of the profile. Figure 3 shows the normalized distortions of the cross-section and the corresponding compensated part shape.

Typically, the calculated process-induced distortions of a composite structure are inverted and fed back into the nominal CAD model, whose geometry is updated accordingly. However, in many cases this complicates the part geometry significantly, as for example flat areas become slightly double curved. This significantly complicates the tool manufacturing process, in particular milling, without a noteworthy benefit for the final part shape. In other words, unnecessary costs are induced. Thus, there is a need for “pragmatic” tool compensation measures in order to compensate the most relevant distortions but also to consider milling efforts and other tool manufacturing processes. This was adopted for the ∠-stiffener at hand. Only the flange-to-web angles were modified, while compensation measures were obtained from the P-approach simulation. The flanges and the web itself remained flat in the CAD model of the tool. Even though the complexity increase of the tool geometry would have been limited for the ∠-stiffener, the concept of “pragmatic compensation measures” for more complex geometries needs further attention in the future in order to improve the parts’ dimensional fidelity while keeping tooling costs low.

Verification and validation

Two sets of stiffeners were produced using the established autoclave injection process. A fibre-volume fraction of 59% was targeted. The shape of the stiffeners was evaluated using a full-field GOM ATOS metrology system. The cross-section evaluations and laminate thickness measurements showed that the prescribed tolerances were met. The results of the cross-section evaluation demonstrated that the developed autoclave injection process made it possible to manufacture parts with a high degree of reproducibility. They also proved the suitability of the applied prediction and the corresponding “pragmatic” compensation measures realized in the tool. A comparison between the weight of the manufactured part and the preform showed that the intended fibre-volume fraction of 59% was achieved with the developed manufacturing concept. Figure 4 shows the flange-to-web angle measurement results of the four manufactured frames. The illustrated angles refer to Figure 1, while the nominal angle is 111.03°. The prescribed angle tolerance of ±0.5° is fully met. As can be seen, all the measured angles are below a tolerance threshold of ±0.1°. This result is convincing as it is in the range of typical part-to-part scattering observed in recent studies on prepreg-based L-profiles [6].

Conclusions

An autoclave injection manufacturing concept for composite ∠-stiffeners was developed and validated as part of a common project conducted by Embraer, Toho Tenax and DLR. The project addressed the challenges of manufacturing aerospace-grade composite structures at reasonable cost with excellent dimensional fidelity. Therefore, the process-induced distortions, which are inevitable for composite structures, were compensated in the tool using numerical predictions derived from the semi-numerical P-approach simulation strategy developed by DLR. The laminate thickness evaluation revealed that aerospace-specific tolerances were met for all manufactured frames. The evaluations of the cross-section shapes underlined that the developed manufacturing concept is suited for the production of parts with excellent dimensional fidelity. Stiffener tolerances of ±0.1° for the flange-to-web angles were met for all the manufactured frames. This is significantly below the prescribed baseline tolerance of ±0.5° that is representative for many composite structures used today. This result indicates that assembly bottlenecks due to severe shimming issues can be avoided in the future. However, designers and engineers need to be aware of the inevitable process-induced distortions of composite structures and the corresponding prediction-based tool compensations, which can be derived using the P-approach, for example. ■

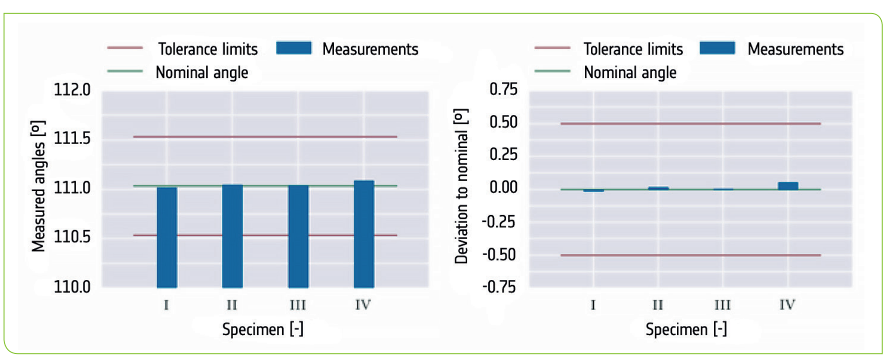

Fig. 4: Cross-section evaluation of the four manufactured composite profiles

More information:
www.dlr.de

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