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Design, optimization and manufacturing of a unitized carbon fiber/thermoplastic wingbox structure

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Manufacture of high performance large composite aerostructures in an out-of-autoclave process using thermoplastic composites that is cost-effective is highly attractive and, at the same time, technologically challenging. Furthermore, the introduction of variable angle tow composites giving spatially variable stiffness properties provides new ways to design high performance composite structures, by redefining the tailoring concept and allowing overall structural performance to be improved. The focus of this paper is the design and the manufacture of a unitized wingbox demonstrator with variable angle tow skin panels and integrated stiffeners. The entire structure is constructed using thermoplastic composite material with an in-situ laser-assisted automated tape placement machine. The design and optimization processes involve load determination, sizing and lay-up optimization of both the stiffener and the variable stiffness skin panels of the wingbox. The design of a reusable modular mold for manufacturing of the wingbox is also described. The interactions between the overall design process and the constraints imposed by the automated manufacturing technology with thermoplastic composites are also highlighted.

I. Introduction

Over the past 25 years, the use of thermoplastic composites (TPC) in commercial and military aircraft has increasingly gained interest. Starting with their first applications with the US military’s F-22 fighter jet landing-gear and weapons-bay doors in the 1980s, to the present time where flying thermoplastic composite parts include the main wing leading edges on the Airbus A380 and A340 passenger jets. Some of the reasons that make this class of material interesting are their potential for fast forming and weldability, their inherently superior fatigue performance and their excellent fire/smoke/toxicity (FST) properties. Furthermore, the potential of these materials to manufacture large thermoplastic aerostructures in a cost effective manner out-of-autoclave (OOA) is appealing.

The wingbox is one of the most complex and heavily loaded primary structures of an aircraft where a minimum number of connections between the different elements is desirable to maximize both weight saving and loading capabilities. To date, the first single-piece composite centre wingbox has been manufactured by Airbus¹ using thermoset material with an autoclave curing process. Although automated methods for laying TPC are proven technology, they seem to be not yet ready for large primary structures. For this reason, the research activity of some aerospace companies focuses on the improvement of the manufacturing processes in order to achieve unitized structures using thermoplastic composites with OOA process and automated tape placement (ATP) techniques.

Another factor to be considered is the introduction of variable angle tow (VAT) composites²,³ that provide new ways to design high performance composite structures. The development of such VAT laminates has broadened the scope for stiffness tailoring by spatially varying the fiber orientations across the planform
of the structure. This additional capability allows the overall structural performance to be improved with respect to straight fiber composite layups. For example, VAT composite plates undergoing compression loads have shown an improvement of up to 50% in buckling load over conventional straight fiber composites.\textsuperscript{4} For these reasons, attention has been given to VAT composites as demonstrated by the recent literature on the subject.\textsuperscript{5–15}

Driven by these interests, the proposed work describes the design, optimization as well as the manufacturing processes of a unitized integrated-stiffened wingbox demonstrator in thermoplastic carbon fiber reinforced PEEK (CF/PEEK) with VAT skin sections. The entire structure is made using an in-situ laser-assisted automated tape placement (LATP) machine. Since no autoclave treatment is needed, the proposed manufacturing methodology is cost and time efficient. It also avoids the limitation that the structure has to fit in an autoclave. Using an approach that winds the wingbox’s skin directly over the stiffeners, the bonding of skin and stiffeners is achieved using a laser beam in-situ consolidation. Therefore, the issues related to the mechanical connections between the different elements are removed. To the best of the authors’ knowledge, a unitized wingbox structure made of CF/PEEK thermoplastic composite with VAT panels is presented here for the first time.

II. Design and optimization

The proposed wingbox demonstrator was chosen to be representative of a medium-range civil aircraft with a maximum take-off weight of $MTOW = 75[t]$ and a wingspan $2b = 36[m]$, as depicted in Fig.1. It is worth noting that as we are dealing with a wingbox manufacturing demonstrator the chosen geometry as well as the chosen loading conditions and the overall design process do not reflect a real wingbox structure for this type of airplane. For these reasons, in this work the design process does not take the standard design procedures and regulations of real flight vehicle structures into account. However, without loss of generality and to deal with a reasonably sized structure, the section of the considered wingbox is located at about 85% of the aircraft’s half wingspan, with a length of $l = 750 [mm]$ in between the two ribs referred to as sections $A$ and $B$ in Fig.1.

![Figure 1. Positioning of the wingbox's section and loads](image)

To define a point-load in the design space, the load distribution over the wing is derived assuming a steady-state horizontal (cruise) flight of the airplane with load factor $N = 1$. The magnitudes of the shear
and bending loads acting on the half-wing are calculated considering an elliptical load distribution over the aircraft’s wingspan. Furthermore, in order to consider as center of the design space a Quasi-Isotropic (QI) composite structure, for the wingbox’s preliminary design the equivalent elastic modulus of a QI composite laminate $E_{QI}$ is considered, namely

$$E_{QI} = U_1 - \frac{U_4^2}{U_1}$$

(1)

where $U_1$ and $U_4$ are the first and fourth invariant properties of a lamina as defined by Tsai and Pagano.\(^{16}\)

Considering the whole wing as a cantilever beam of length $b$, the shear force $T_3(X_2)$ and the bending moment $M_1(X_2)$ along the wing are calculated performing the integrals

$$T_3 = \int q(X_2) dX_2$$

(2a)

$$M_1 = \int q(X_2) X_2 dX_2$$

(2b)

where $X_2$ is the coordinate spanning the wing with its origin at the wing tip and $q(X_2)$ is the elliptical lift force distribution along the wingspan, which is expressed as

$$q_3(X_2) = \frac{q_0}{b} \sqrt{2bX_2 - X_2^2}$$

(3)

where $q_0 = \frac{2MT_{TOW}}{b^2}$ is the value of the load distribution at the wing’s root. The integration’s constants involved in Eqs.2 were evaluated imposing zero values for both $T_3$ and $M_1$ at the wing tip. Assuming a constant value for the ratio between the moment $M_1(X_2)$ and second moment of area $I_1(X_2)$ along the wingspan, the elastic-curve equation gives

$$E_{QI} \frac{d^2u_3}{dx_2^2} = \frac{M_1(X_2)}{I_1(X_2)} = a = \text{constant}$$

(4)

where $u_3(X_2)$ is the transverse displacement of the generic wing section. By integrating Eq.4 twice and setting to zero the transverse displacement and the rotation of the section located at the wing root in order to evaluate the integration constants, one obtains

$$u_3(X_2) = \frac{1}{2E_{QI}}(aX_2^2 - 2abX_2 + ab^2)$$

(5)

In order to choose a reasonable value for the constant $a$, considering also the chosen flight condition, the maximum transverse displacement of the wing tip was chosen. This implies that the function that describes the required second moment of area of the generic wing section along the wingspan can be obtained using Eq.4 as

$$I_1(X_2) = \frac{1}{a}M_1(X_2)$$

(6)

The required second moment of area of the section located at 85% of the wingspan was then evaluated using Eq.6. In order to model simpler geometries, the considered wingbox segment is not tapered and a constant wingbox section along the wingspan is considered. Hence, considering the length $l = 750 [mm]$ of the wingbox segment shown in Fig.2, the appropriate values of the shear force and the moment acting on the wingbox were evaluated by integrating Eqs.2 in between the two wingbox sections $A$ and $B$ and by imposing the equilibrium condition at the $B$ section. Under these assumptions, referring to Fig.2, the wingbox section $B$ is considered to be fully clamped and the wingbox undergoes a vertical shear load $F_A = 23.8 [kN]$ along the $X_3$ axis and a bending moment $M_A = 14.3 [kNm]$ along the $X_1$ axis in section $A$.\(^{3}\) of 15

American Institute of Aeronautics and Astronautics
As briefly described in section I, the key idea of this work is to manufacture the entire structure using LATP without any autoclave treatment. The TPC tape is laid over a wingbox mold by winding the wingbox skin directly over the stiffeners previously made using the same ATP manufacturing process, as described in companion work by Peeters et al.\textsuperscript{17} Hence, the bond between the panel and the stiffeners is obtained with a laser beam in-situ consolidation, as described in section III. The laser-assisted ATP manufacturing (LATP) equipment used in this work consists of a laser-assisted tape placement head (AFPT, GmbH) attached to a robotic arm (Kuka, KR240 L210 – 2), as shown in Fig.3. Although this manufacturing process represents the state-of-the-art manufacturing technology with TPC tapes, there are some limitations that constrain the overall design process. Some of the most important constraints were related to the minimum length of tape that can be laid down with LATP and, for effective winding of the closed section, the minimum dimensions of the wound section. In fact, for this last case a release mechanism for the mold is a necessary requirement. This need arises due to the thermal contraction of the wound material during the laying process that causes considerable compression forces on the mold, making its extraction after manufacturing difficult. More details on this manufacturing aspect are discussed in companion work by Peeters et al.\textsuperscript{17} For these reasons the geometrical dimensions of the stiffeners shown in Fig.2 were chosen by considering both the actual loads acting on the wingbox and the LATP winding manufacturing constraints.
To determine the number of layers in the skin and stiffener of the wingbox, a sizing exercise was undertaken. To perform the sizing, the lay-up was fixed to $[0/90/−45/45]_s$, and the thickness of the different layers was scaled in such a way that the total thickness amounted to a certain number of layers in the skin and stiffener. This was done for a quasi-isotropic (QI) case (i.e., all layers the same thickness), and for the case where 60% of the layers is in the longitudinal direction ($0^\circ$), 30% in the $±45^\circ$ direction and 10% in the circumferential direction ($90^\circ$). The stiffener was designed to have at least the same thickness as the skin. The sizing parameter was the buckling factor: this had to be as close as possible to one. Furthermore,
in order to avoid shear buckling of the two spar webs of the wingbox, four extra layers are introduced in the layup for these regions. The angle for these extra layers was chosen to be 0° by considering the fact that other tow angles would require a cut within the laminate leading to fibre discontinuity and additional manual work. By performing a layup optimization subjected to these constraints it was found that 11 layers for the skin and 12 layers for the stiffener was the optimal option. For the sake of completeness, the layup $[-45/45/0/90]_s$ was also considered in the optimization procedure, both for QI and different combinations of the $60-30-10\%$ of fibers in a specified direction. For all of the discussed cases, the first buckling load factor for the considered loading condition was around 1, with first buckling mode occurring in the bay panels of the compressed part of the wingbox in between the stiffeners. The final layup with straight fibers chosen as baseline for the preliminary design is shown in Table 1.

<table>
<thead>
<tr>
<th>Skin bay</th>
<th>Skin</th>
<th>Stiffener</th>
<th>Spar web</th>
</tr>
</thead>
<tbody>
<tr>
<td>$90/\pm35/0/\pm45$</td>
<td>$90/\pm35/0/\pm45$</td>
<td>$90/45/02/-45/0$</td>
<td>$90/\pm35/03/\pm45$</td>
</tr>
</tbody>
</table>

In order to improve the local buckling behaviour of the panels of the wingbox located in between the stiffeners, a steered VAT layup is considered in these regions, as shown in Fig. 4. However, in this case some constraints related to the manufacturing process have to be considered. These limitations relate to the actual possibility to lay the TPC tape with high quality of the interlaminar bonding using only straight-line or circular motions of the LATP head. This consideration means that the considered steered layup for the panels are obtained by performing two successive circular movements of the LATP head with the same radius of curvature. As a result, to avoid tape overlaps in other parts of the wingbox where the fiber angle is constant some gaps were admitted in the panels with a steered layup. To investigate the effects of these steering-induced manufacturing features, three different steering radii were considered during the design process, namely $R = 400[mm]$, $R = 600[mm]$ and $R = 800[mm]$. Fig. 5 shows the manufacturing test performed for these three cases. More details on the manufacturing of these VAT panels are discussed in companion work by Clancy et al.18

![Figure 4. VAT wingbox’s skin panels](image-url)
Following these considerations and the results obtained from the manufacturing test, a steering radius of $R = 400 \text{ [mm]}$ for the layup of the wingbox skin was chosen. The final layup for each part of the wingbox with VAT skin sections is shown in Table 2, where the notation introduced by Gürdal and Olmedo\cite{3} is used. The zero degree fiber orientation is defined as parallel to the longitudinal direction of the wingbox. All of the layups consist of 0.1875 mm thick tows whose reference material properties are shown in Table 3.

### Table 2. Layups considered for the wingbox with VAT sections.

<table>
<thead>
<tr>
<th>Skin bay</th>
<th>Skin</th>
<th>Stiffener</th>
<th>Spar web</th>
</tr>
</thead>
<tbody>
<tr>
<td>90/[(0 ± 52[35])/0/ ± 45] \text{s}</td>
<td>90/[±35/0/ ± 45] \text{s}</td>
<td>[90/45/0_2/ − 45/0] \text{s}</td>
<td>90/[±35/0_3/ ± 45] \text{s}</td>
</tr>
</tbody>
</table>

### Table 3. Material properties of the tow.

<table>
<thead>
<tr>
<th>$E_1 \text{ [GPa]}$</th>
<th>$E_2 \text{ [GPa]}$</th>
<th>$G_{12} \text{ [GPa]}$</th>
<th>$\nu_{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>135.0</td>
<td>7.54</td>
<td>5.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Note that the chosen VAT layup does not represent an optimized variable stiffness layup for the chosen load-case, rather it serves to demonstrate the potential of the present manufacturing technology and the advantages offered by such VAT laminates. In order to compare the two designs, finite element analyses were performed for both straight fiber and VAT layups. Abaqus FE software with $S4R$ shell elements were used. Offsets of the layup properties were used in the FE model to ensure continuity is consistent along the edges of contiguous elements with different thickness and stacking sequences. To model the fiber angle distributions in the skin bay sections, a subroutine was implemented to generate meshes where each element has an independent constant fiber orientation. Hence, 42 different layups were considered for the VAT wingbox. A structured mesh with 8,100 square elements, with a total number of 1,437,240 DOFs, were
used as they provided converged results. To ensure that only elastic buckling without failure was expected, linear static analysis was performed for the maximum loading condition. The principal strains were checked and the maximum principal strain found in any layer was $\epsilon_{ij} \leq 2500 \mu \varepsilon$, which is considered to be acceptable. The results from the linear buckling analyses are shown in Table 4 in terms of the first buckling factor $\lambda_1$. These results show that the use of variable stiffness layups significantly improve the buckling capability of the wingbox structure. For this particular case, an improvement of the first buckling factor of 14.5% with respect to the straight fiber configuration was obtained. The first buckling mode of the VAT wingbox is shown in Figure 6. The authors would like to emphasise that the chosen VAT layup does not represent an optimized layup, rather it serves to demonstrate the potential of the present manufacturing technology and advantages offered by such VAT laminates.

<table>
<thead>
<tr>
<th>VAT layups</th>
<th>Straight layups</th>
<th>Diff%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_1$ = 1.10</td>
<td>$\lambda_1$ = 0.96</td>
<td>14.5</td>
</tr>
</tbody>
</table>

III. Manufacturing

The proposed wingbox demonstrator was manufactured using the LATP process. Namely, the wingbox skin is wound around a mold using a laser beam in situ consolidation process.
As shown in Fig. 7, the mold is modular and it can be reused for other thin-walled closed section stiffened structures. All of its parts were assembled using bolts (no welding or adhesive), therefore it disassembles readily once the wingbox is manufactured.

Referring to Fig. 7, the mold is assembled around a steel shaft (A) inserted into motorised chucks which rotate the mold in time with the Kuka robot as the LATP head lays down the TPC material. Two end plates (B) are placed on to the shaft and are connected to two side plates (C). These four plates construct the main frame of the mold and act as supports for the top and bottom of the mold, consisting of four edge plates (D) and four top/bottom plates (E). Between the top/bottom plates as well as between the top/bottom edge plates there are the stiffener supports (F) which facilitate the correct placement of the stiffener into the wingbox mold. In order to avoid bending of the side plates (C), top/bottom plates (D) and edge plates (E) as the LATP lays the material, reinforcement ribs (G) were inserted into the core of the mold. The ribs are split into two parts, to assist in collapsing the mold once the wingbox has been manufactured. To prevent the support ribs from collapsing during the winding process they are reinforced with the rib supports (I). Furthermore, the reinforcement ribs are kept in position on the shaft using collars (H). The collars have two holes to insert locating pins to connect them to the shaft and the ribs. Finally, the middle rib is connected to the side plates and top/bottom plates using the connectors (L) in order to increase the stiffness of the overall mold and to prevent its parts from bending or moving as the mold rotates in the chucks. To remove the finished wingbox from the mold, the two end plates (B) were removed by undoing the bolts securing them. Once the end plates are removed this gives access to the reinforcement ribs (G), their supports (I) and
the positioning collars (H). Once collars were removed, the bolts of the rib support were undone to allow the first rib to be removed. Afterwards, the middle rib is accessible and the same process is followed with the addition of removing the connectors (L). Once the final reinforcement rib was removed, the top/bottom layers D and E as well as the stiffener support F were removed. Finally, the shaft (A) and side plates (C) were removed.

The wingbox stiffeners were made with a prior LATP process as described in companion work by Peeters et al.\textsuperscript{17} and positioned in the wingbox mold as shown in Fig.8 and in Fig.7. The connection between the stiffeners and the skin was achieved when the first layer of the skin is laid down by the laser beam in situ consolidation process. Using this manufacturing process, a skin-stiffener manufacturing bonding test was performed for a stiffened panel, as shown in Fig. 9. The details of the skin-stiffener bonding are discussed in companion work by Bandaru et al.\textsuperscript{19}
Particular attention was dedicated to the positioning of the stiffeners into the mold. In order to have a flat surface in the skin-stiffener overlapping regions, the stiffeners were shimmed to get them flush with the outer surface of the mold. Small gaps occurred along the lateral sides of the stiffeners and the mold due to the corners of the stiffeners being rounded. However, it was observed that when the first layer was wound over, the tension in the tows was sufficient to bridge the small gap. Finally, a support structure was put in place at the stiffeners’ ends to keep the stiffener flush with the mold and thin brass parts were added to protect the support structure from the laser. However, since the first 150 mm is cut off and discarded, as mentioned in companion work by Peeters et al.,\textsuperscript{17} the perfect alignment of the stiffener termination was not deemed to be a problem.

As shown in Table 2, the first layer is a 90° layer meaning it is wound around the mold. This process can be done with a single tow. However, in the present case the spool length of 200 m was not sufficiently long to wind the whole length of the wingbox. Therefore, two tows were used and a gap of one tow-width remains while placing the first tow, as shown in Figure 10. Subsequently, the layer was completed with the second tow, as shown in Figure 11.
Following the chosen layup, the second and third layers have steered sections. As explained in companion work by Clancy et al.\textsuperscript{18} the steering process was done using a circular motion. A picture showing the second layer partially complete is shown in Figure 12. Referring to Figure 12, the different color appearance of the tows is related to the fact that the tows that start in a corner are laid down first using a new roller for the tow deposition. The complete third layer is shown in Figure 13. It should be mentioned that for the third layer some tows did not initially bond with the base material. This happened due to the fact that the terminations of the stiffeners bent slightly under the pressure of the roller causing the bond of the tow to the substrate to fail. However, since the portions where the tows do not bond are within the cut-off and therefore discarded part of the wingbox, it did not pose a problem for the final demonstrator. As expected, gaps appear between the stiffeners where the fibers are steered.
In order to have a better bonding surface, the first 100 mm of the wingbox was wrapped with a 90° layer before laying down layer four. A good bond was obtained for most of the tows as shown in Figure 14. Only two tows of the fourth layer bonded too far in the tool and had to be removed and redone. The remainder of the layers did not pose any problems. It should be mentioned that before the 0° plies were laid down it was necessary to wrap the cut-off region of the wingbox with a 90° layer to have a better bonding surface, which was the only change that was made in the manufacturing procedure. The finished wingbox once removed from the mold is shown in Figure 15.
IV. Concluding Remarks

A unitized wingbox demonstrator with integrated stiffeners and variable stiffness skin sections made of CF/PEEK thermoplastic composite has been presented. The wingbox is a representative of a medium-range civil aircraft with $MTOW = 75000\,[kg]$ at about 85% of the aircraft’s half wingspan. The load distribution over the wing was derived assuming a steady-state horizontal (cruise) flight of the airplane and the magnitudes of the shear and bending loads acting on the wingbox were derived considering an elliptical load distribution over the wingspan. Therefore, the loaded $A$ section of the wingbox undergoes a vertical shear load $F_A = 23.8\,[kN]$ and a bending moment $M_A = 14.3\,[kNm]$. In order to consider elastic buckling phenomena and show some of the advantages offered by VAT skin section, the buckling of the skin at the maximum design load was considered. For this particular case, comparing the results of the
FE analyses for both the classical straight-fiber and the variable stiffness configurations, an improvement of the first buckling factor of 14.5% was predicted. The manufacturing procedures discussed shows the LATP manufacturing technology we have developed for variable stiffness and integrated stiffener panels. The manufacturing constraints that influenced the design and optimization processes and that are related to the state-of-art of the laser assisted tape placement have also been discussed. Furthermore, the design of a modular and reusable mold for the wingbox was described. This mold allows for future development of manufacturing different wingbox sections and stiffened panels with various stiffeners geometries. The proposed “winding” approach for the wingbox manufacture allows the bonding of skin to stiffeners to be achieved using the laser beam in-situ consolidation process. Since no autoclave treatment was necessary, the proposed manufacturing methodology is time efficient and avoids the limitation that the structure has to fit in an autoclave. To the best of the authors’ knowledge, a unitized wingbox structure made of TPC with VAT panels is presented here for the first time.

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References