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Thermoplastic Composite Stiffener Design with Manufacturing Considerations

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Fiber reinforced composite materials are finding increasing application in aerospace structures due to their superior specific properties. Aerospace structures make widespread use of stiffening elements, such as stringers, for example in the wingbox or the fuselage. Sizing of stiffeners to fulfill strength, stiffness and manufacturing considerations is a significant challenge for aircraft designers. This paper proposes a novel manufacturing approach using winding and laser-assisted tape placement (LATP) to manufacture an omega-shaped stiffener. The stiffener design is used as the stiffening elements in a wingbox; the sizing of the stringer is based on the optimized buckling response of the wingbox, with manufacturing constraints also taken into consideration. The stringer is manufactured by LATP winding over a novel collapsible tool. The tool utilizes a low-melt alloy as a spacer, which can be removed post-process by exposing the mold to the alloy melt temperature, which is below the glass transition temperature of the thermoplastic composite material. Manufacturing tests have shown that using the new mold design leads to repeatable stiffeners of the correct dimensions. Characterisation tests have shown that the strength of the corners has to be checked in future work. The bond strength of the stiffeners is satisfactory.

I. Introduction

Composite materials are finding increasing application in large commercial aircraft due to their superior specific properties,¹ noting the Boeing 787 and Airbus A350 both contain over 50% by weight of composite materials.², ³ Aerospace structures make widespread use of stiffening elements, such as stringers, for example in the wingbox or the fuselage. Sizing of stiffeners to fulfill strength, stiffness and manufacturing considerations is a significant challenge for aircraft designers.

In addition to the shape of the stiffener, the cost of manufacturing should also be taken into account.⁴ Kassapoglou optimised different stiffener shapes, and their attributed costs were evaluated for a stiffened panel under combined compression and shear load. The manufacturing method considered was manual lay-up where cost was mainly attributed to the expected time to cut, lay-up and bag the stiffener. The outcome showed that the weight- and cost-optimum do not coincide. When optimising for weight, with a penalty for cost, T-shaped stiffeners were found to be optimal.⁴ However, the manufacturing method has a significant influence on the cost parameter; when using automated lay-up, or removing the need to bag the stiffener, the cost calculation significantly changes.

Another important consideration when manufacturing a stiffener is the type of mold used. A study on hat-stiffeners, also known as omega-shaped stiffeners, compared the use of metal, rubber and inflatable molds to manufacture co-cured stiffened panels. As a reference, a flat panel was made, to which a stiffener was bonded using secondary bonding. When using the metal mold, the geometrical accuracy of the plate was the same as the reference one, and the stiffener also had the intended shape. When using the rubber mold,
the pressure was found to be mostly uniform in finite element analyses, but the geometry of the plate was slightly less accurate than the reference. Finally, when using the inflatable mold the pressure was also found to be uniform, but there was a large curvature in the final plate which was attributed to residual stresses. The pull-off tests revealed that the co-cured panels had a higher failure strength than the secondary bonded reference plate, with the inflatable mold giving the best performance in terms of bond strength among the co-cured panels. This result was also found numerically: finite element results showed that integrally stiffened structures have a 3–5% higher bond strength compared to co-curing, while mechanical fastening leads to 19–25% lower bond strength than integrally stiffened structures.

In addition to the aerospace industry, ships also use composites with omega stiffeners. The main difference is that glass fiber-reinforced polymer (GFRP) is used rather than carbon fiber-reinforced polymers (CFRPs), which are more common in aerospace engineering. A popular approach using GFRP is to first make the skin, then add a non-structural layer of foam, and lay the stiffener over this foam.

PRSEUS is a more complicated concept, developed by NASA, which uses both stiffeners and stringers in a one-piece co-cured panel. A pre-cured rod is used for the stringers, around which the stringer flanges are stitched. The stiffener is laid down over a foam core, where slots are present for the stringer to run through, as can be seen in Figure 1. The whole part is then stitched to a plate and cured. Even though this is a strong structure, it is relatively complicated to manufacture and needs to be cured after manufacturing.

![Figure 1. Schematic view of the PRSEUS concept](image)

A significant disadvantage of using thermoset materials is the need for further thermal processing using an autoclave. One way to avoid this limitation using thermoset material is with liquid resin infusion. Blade stiffeners were made of preforms that were kept together using either an epoxy powder or stitches. When using the powder, the preform is placed in a heated oven of around 100 degrees for 30 minutes. Afterwards the stiffeners can be handled easily and are placed on top of a plate and the complete preform is infused in one operation. Even though the autoclave is avoided, both the bagging, necessary for the infusion process, and the infusion itself are time-consuming.

When using thermoplastic materials, a stiffener can be connected to the surrounding structure using induction welding, removing the need to use the autoclave or infusion. Induction welding of thermoplastic material has been the subject of many research papers over the last thirty years. Another way to connect a plate to the stiffeners is to place the stiffeners in place and bond in-situ when laying down the first layer.

To manufacture an open-form stiffener, pressing the material in the desired shape is one possibility. Match die forming can be used to obtain L-shaped stiffeners out of thermoplastic material. Another approach is press forming thermoplastic sheets into the desired forms. Tests have shown that this is a fast and repeatable process, however, the fiber angle orientation after pressing is difficult to predict accurately.

A manufacturing process to obtain a closed-form section is filament winding. A key issue is heating the pre-impregnated thermoplastic tapes to the right temperature. Possibilities include direct flame, hot gas, infra-red radiation and a laser. For the fastest manufacturing speeds, a laser is the best option, while infra-red radiation leads to a lower process-cost. Another important parameter is the tape tension while laying down the tape. This has a large influence on the residual stress in the final product.
Instead of using pre-impregnated tows, combining on-line impregnation and filament winding is also possible. Initially, more voids were found using this methodology. More recently, the technology was improved, and the quality of the final product was comparable to using pre-impregnated tows. An advantage of on-line impregnation is that it allows local fibre volume fraction variation. The quality of the on-line impregnation was shown to be comparable with pre-impregnated tows for speeds up to $15m/min$.

In the current work, an omega-stiffener is sized and manufactured out of thermoplastic material using winding and laser-assisted tape placement (LATP) meaning in-situ consolidation is achieved. This manufacturing process has not been reported in literature to the authors’ knowledge. Contrary to most other stiffeners, we have chosen a closed-section stiffener which is manufactured using a novel collapsible mold. After manufacturing of the stiffener, a skin can be laid over them, creating an integrally stiffened structure without the need for an autoclave, vacuum oven consolidation, or induction welding. This same principle can later on be applied in a wingbox, as discussed in companion work by Oliveri et al.

**II. Sizing of the stiffener**

For this work closed-section omega-stiffeners were selected. To describe this shape, three variables are necessary: top, bottom, and height, as indicated in Figure 2. The bottom of the stiffener is defined as the side that will be attached to the surrounding structure.

![Figure 2. Dimensions of the stiffener.](image)

The omega-stiffeners are to be used as stiffening elements in a wingbox, which is discussed in companion work by Oliveri et al. and shown in Figure 3. The height of the wingbox is chosen to be $240mm$, hence the stiffener height needs to be considerably smaller than this. On the other hand, since winding in combination with LATP is the chosen manufacturing strategy, the height cannot be too small: the mold has to be sufficiently stiff during manufacturing. The bar around which the mold rotates was set to be at least $25mm$ in diameter to avoid excessively large deflections under the weight of the mold and the pressure of the fiber placement machine. Furthermore, the mold itself should be at least $3mm$ thick so as to not deflect under the pressure of the fiber placement machine. To allow for variations in stacking sequence, it was decided that the height of the outside of the finished stiffener should be $40mm$.

Once the height was set, only the top and bottom length of the stiffener had to be sized. For the analysis, the minimum size of both the top and bottom was chosen to be the same size as the height, $40mm$: an omega-stiffener that is less wide than its height was considered unfeasible. The maximum width was set to twice the height, $80mm$: any wider was considered too wide. As a final constraint, it was decided that the bottom of the stiffener has to be at least as large as the top of the stiffener: traditionally the bottom of an omega-stiffener is wider than the top. Overall, these considerations provide good levels of torsional stiffness and reduce inter-stiffener distance, thereby raising buckling loads and ultimately improving structural efficiency. To limit the number of analyses, the top and bottom length were changed in steps of $10mm$, requiring 15 possibilities to be checked.

To determine the optimal shape of the stiffeners, the buckling load of the wingbox with stiffeners of different sizes was calculated. The middle of the bottom of the stiffeners are always located at 125, 375, and 525mm from the side. The loads chosen were the same as those applied to the wingbox: a vertical shear force of $31kN$ and a moment of $16kNm$, applied using in-plane compression on the top side, and tension on the bottom side. The material properties used are for the Toho material, as listed in Table 2. Buckling was constrained to be in the plates, not in the stiffener. To ensure this, an equal number of layers in the skin and stiffener were used. The lay-up chosen was $[0/90/-45/45]_s$. The thickness of all layers was scaled to obtain a specific total thickness. The absolute thickness is not important in the study since it is a
linear analysis: scaling the thickness will not change the relative difference between the different geometries. For clarity, the calculations were repeated after sizing of the wingbox with a thickness equal to 16 layers such that the buckling factor is approximately 1. In this case the lay-up can be physically interpreted as $[0_2/90_2/-45_2/45_2]_s$.

The result of the buckling factor calculations is shown in Figure 4. From this figure it can be seen that the main influence is the length of the bottom of the stiffener. These results were as expected: the wider the bottom of the stiffener, the smaller the plate in between, where buckling occurs. Furthermore, it can be deduced from this figure that the length of the top of the stiffener has a small influence, hence to save weight it should be chosen to be as small as possible.

Another aspect that must be taken into account is that during LATP winding, the head is almost stationary in the corners: while the mold is rotated the distance traveled is only the length of the rounded corner. The laser is controlled by a feedback loop based on the temperature of the thermoplastic material, hence the laser power changes during the rotation. However, from previous experience it is known that an acute angle of the mold may lead to manufacturing issues: either the laser does not power down soon enough and the fibers get burnt or the laser powers down too much and part of the fibres are not heated enough. To avoid this, the top was made $60\,mm$, and the bottom $80\,mm$, making the angles in the stiffener not too acute.

Figure 3. Dimensions of the wingbox.

Figure 4. Result of the stiffener sizing.
III. Mold design

Conflicting requirements posed significant challenges for the stiffener mold design. The mold should be sufficiently stiff to withstand the pressure of the fiber placement head pressing down on it, as well as the pressure of the composite material as it cools down after placement, but it should also be sufficiently easy to remove the mold after manufacture. It was decided that a collapsible mold offered the best option for demolding without damaging the stiffener.

To make the mold collapsible, two options were considered: one, hinges located in certain edges; two, small gaps in the edges that make the mold smaller once the support is taken away. The disadvantage of hinges is that to get the sides of the mold to collapse, some force is required. This requirement has two implications: one, collapsing the mold then unintended damage to the stiffener may result; two, the mold becomes damaged beyond repair for future use. For these reasons the second option was chosen: making small gaps in the side of the mold such that it collapses once the support is removed.

Three 2 – 2.5mm gaps were inserted in the mold, as shown in Figure 5. The two gaps on the inclined sides allow the top section to collapse down, while the bottom gap allows easy removal of the lower part of the mold. Since the thermoplastic tows are under a small tensile force during manufacture, the small gaps are expected to have little effect on the final product. The roller that presses the tapes on the mold has a diameter of 80mm, meaning it cannot ingress deeply into the gaps of the mold.

![Figure 5. Schematic side view of the mold (all dimensions in mm).](image)

The next challenge is to design the support that keeps the mold in place during manufacture, but is easy to remove afterwards. It was decided to make the cut-out in the center of the mold slightly larger than the shaft, and fill the excess and the small gaps with material that would be easy to remove. As for the material choice, a water-solvable material was considered, but since the necessary thickness was thin (2mm), the material was considered to be too brittle. Instead, a low-melt alloy was selected. The selected alloy melts at 75°C, well below the glass transition temperature of the thermoplastic material, which is around 140°C. After manufacturing, the mold and stiffener are placed in an oven, and heated to about 80°C, causing the alloy to melt and flow out. This leads to the mold collapsing such that it is easy to remove.

The complete stiffener mold was required to be 1.2m long. However, tool manufacturing restrictions...
prevented the mold from being produced in one piece: milling steel or aluminium over such a distance with the tight tolerances necessary is difficult and expensive. To ease manufacturing and reduce cost, the mold is made out of 4 parts that are attached to each other using 2 pins per part, as shown in Figure 6. This design has the added advantage that the mold becomes modular: if a smaller stiffener is to be manufactured, only 2 or 3 out of 4 parts can be used.

![Figure 6. Mold connection point with low-melt alloy spacers.](image)

The final consideration involves the corner radii, which need to be sufficiently large to prevent the LATP head from becoming stationary during mold rotation: while the mold rotates the distance traveled by the head is the distance of the rounded corners. Hence, if there is no radius, the head does not move while the mold rotates. Based on our previous experience with manufacturing closed-form parts and the angles in the mold, the radius was set to 4 mm.

### IV. Initial manufacturing results

When winding during LATP, only a 0° ply (i.e., fiber in longitudinal direction) is exactly 0°: all other angles are slightly changed. This change is necessary to avoid gaps or overlaps on the stiffener: after one complete revolution, the distance moved in the longitudinal direction should be a multiple of the tow width such that by winding multiple tows the complete stiffener is covered without any overlaps or gaps. For example: a 90° ply means that one winds around the stiffener, but if exactly 90° is used, the ply would have to be cut after one revolution to start again next to it. Instead, the angle is made slightly smaller such that after one revolution one ends up right next to the ply already laid down. The first layer is not 90°, but 88.1°. In this way a 90° layer is one continuous tow leading to better load carrying capability and easier manufacturing. The same is done for 45° plies: more than one tow is necessary, but the principle remains the same.

For the initial manufacturing test, a stiffener with a length of 300 mm was made. This sample provides proof of concept and highlights possible improvements for future manufacturing without using an excessive amount of material. The lay-up was chosen to be [90/45/−45/0]S, such that all major fiber angles are utilised. The first layer needs to be 90° because the thermoplastic material does not stick to the mold, hence...
it has to be wrapped around, with the start and end of the tow manually stuck to the mold with tape to provide sufficient tension. During manufacturing the tow is under tension and conforms well to the mold. The linear tape feed speed was set to $3 \text{ m/min}$ since the mold is relatively small, and at each corner the speed is reduced to allow the mold to be rotated.

To assess the effect of the gaps in the collapsible mold surface, it was decided to stop winding after one layer and cut the stiffener to examine it for potential defects. The result is shown in Figure 7. The locations of the gaps in the mold are visible after manufacturing, but the indent is small. It is expected this will not be seen in the final part. Sometimes a small gap appears between the tows. These are caused because of small differences in the width of the tow, which was slit by hand from 12 to $6 \text{ mm}$, meaning there are slight variations in the width over the length of a tow. Overall, no significant problems are seen in this layer, so manufacturing of the complete stiffener was deemed feasible.

![Figure 7. View of the first layer that was cut of the mold.](image)

The first layer was laid down again without problems. The same holds for the second and third layer, $45^\circ$ and $-45^\circ$, which were laid down without manufacturing problems. The fourth layer, $0^\circ$, did cause some issues: the start of the $-45^\circ$ layer was not sufficiently smooth for the $0^\circ$ layer to bond well to it. Some tows did bond after a short distance, others did not bond at all. These tows were repeated, so in the end the layer was complete. Since the fifth layer was again a $0^\circ$ layer, a change was made: the first few centimeters of the stiffener were wrapped in $90^\circ$ fibers to give a smooth surface to initiate laydown. With this change, the fifth ply was laid down without any problems. The final three layers were laid down without any new issues appearing.

After manufacture, the complete mold and shaft were placed in an oven, and heated to around $80^\circ C$. The alloy melted, and poured out, as shown in Figure 8. This caused the mold to collapse as designed, and the stiffener readily released. A view of the final product is shown in Figure 9.

V. Changes after initial manufacturing trials

A different material system, from another material supplier, was used for the actual wingbox demonstrator. Hence, another manufacturing test was done with the major fiber angles. To have a reasonable and fair comparison between both materials, the $0^\circ$ tows were placed directly on top of the $45^\circ$ ply. This time all tows were laid down without problems.

It was noted that at the start, the tows did not bond immediately: it could take a few centimeters before the tows bonded. The tabs, which appear because the first part of the tape is not heated by the laser, lifted at the start. These tabs were sometimes snagged by the roller, folded back, and ended up in the piece. A possible solution is to manually cut the tab after each track, but this is time-consuming. When it was noticed that a tab could end up in the part, it was cut, but this is sometimes hard to see, so it cannot be guaranteed there will be no tabs ending up in the final piece. To avoid the tabs and have a good bond in throughout the final stiffener, it was decided to discard the first $150\text{ mm}$ from the stiffener.

As a final remark, it should be noted that in a $0^\circ$ ply, an overlap or gap will appear: the circumference
of the mold is not an exact multiple of the tow width. The gap or overlap appears at the location where the first tow is laid down. Since the bottom of the stiffeners is to be bonded to the wingbox, this surface should be flat, hence the first tow should not be laid down here. The first tow should always be in the same location in plies that are symmetric to each other. In plies that are not symmetric to each other, the location is changed to avoid multiple overlaps or gaps occurring in the same place.

VI. Final manufacturing results

During the manufacture of the final stiffeners no further problems were encountered: all tows bonded well, sometimes a tab ended up in the part but only in the part that is cut off. The quality of the stiffeners is visually good: no obvious defects can be seen. The repeatability of the process is also good: all stiffeners visually look to be identical, as shown in Figure 10.

The only disadvantage of the collapsible mold is the time required to disassemble the mold and remove the stiffener and finally reassemble for the next stiffener (typically, a process that takes two to three hours). Heating the mold to the required temperature takes about half an hour. Before mold reassembly, the mold and steel shaft need to cool before the low-melt alloy spacers can be applied to avoid thermal induced
For a 0° layer, the corners were not always well-bonded. This problem was due to the roller not conforming to the complete tow: the radius of the corners is only 4mm, a tow is 6.35mm wide so the roller would have to deform significantly to comply completely with the mold. An example of a tow that did not bond well can be seen in Figure 11(a). When the bond was not achieved, the tracks of the layer were repeated with the roller applying pressure and the laser providing a constant power, but without material going down. The temperature reached was approximately 375°C meaning the material is molten and can bond to the layer underneath. Because all tracks are repeated, the roller presses on the part it did not conform well with during the previous track. Since the laser is also heating this material, a good bond is achieved. A picture of the stiffener after the laser passes over can be seen in Figure 11(b).

VII. Characterization tests

To check the quality of the stiffener, two characterization tests are done. The first, an Interlaminar Short Beam Shear test is performed to determine the interlaminar bond characteristics. The second test determines the strength of the corner: L-shaped parts extracted from the corners of the stiffener are unfolded to determine the strength of the corner.

The bond strength is determined using an Interlaminar Short Beam Shear test, following the ASTM Standard D2344. The test specimens were extracted from the inclined sides of the stringer and have a thickness of 1.24 mm, as measured after manufacturing. The dimensions of the test specimens are 20 by 10 mm. The test fixture is shown in Figure 12.

The result of the 5 samples that were tested are shown in Table 1. The thickness, load at initial failure,
which is the load just before the first drop in the load-displacement diagram, and maximal load are reported in this table. Interlaminar shear strength (ILSS) was calculated using the equation prescribed in the test standard:

\[ ILSS = \frac{3F_{\text{max}}}{4 \cdot b \cdot h} \]  

where \( F_{\text{max}} \) is the maximum force, \( b \) is the width and \( h \) is the thickness of the sample. However, the lay-ups used were non-standard, i.e. they were multi-directional rather than uni-directional. The ILSS calculation was used to compare the bond strength of the test specimens. Observing the results, it can be seen that the scatter is not excessively large.

The values found for the interlaminar stress are fairly low, but this was the first trial with the material. Furthermore, in companion work by Bandaru et al.\cite{24} subsequent testing indicated that initial machining of the samples by water-jet cutting may have induced delamination in the specimens. Specimens machined using a diamond blade cutter saw a significant increase in ILSS strength to 46 MPa.\cite{24} As a result, the ILSS of the stiffener alone must be at least as high as the stiffener-skin combination. Hence the bond strength was deemed to be satisfactory.

**Table 1. Overview of the results of the short beam tests.**

<table>
<thead>
<tr>
<th>sample number</th>
<th>thickness [mm]</th>
<th>load at initial failure [N]</th>
<th>maximum load [N]</th>
<th>ILSS at initial failure [MPa]</th>
<th>ILSS at maximum load [MPa]</th>
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<tr>
<td>1</td>
<td>1.25</td>
<td>146</td>
<td>188.4</td>
<td>8.37</td>
<td>10.8</td>
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</tr>
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<td>170.4</td>
<td>8.94</td>
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</tr>
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<td>9.67</td>
</tr>
<tr>
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<td>7.27</td>
<td>14.69</td>
<td>0.47</td>
<td>0.72</td>
</tr>
</tbody>
</table>

The residual stress in the stiffener can be estimated by the amount of spring-back when the stiffener is cut open. As can be seen in Figure 13 the spring-back is relatively small. This indicates relatively low residual stresses in the corners.

The second part of delamination strength testing is done by taking specimens from the uncut top-side corner of the stiffener. These specimens are unfolded in a 4-point bend test, following ASTM Standard D6415,\cite{25} as shown in Figure 14. The specimen dimensions had to be changed from the standard recommendations because the stiffener was too small: the maximum length of the sides is 30 mm since they are equal. Furthermore, the radius used in the stiffeners is 4 mm, not 6.4 mm as defined in the standard, the thickness is too low according to the standard, and the angle is not exactly 90°. To comply as closely as possible to
the test, all dimensions are roughly halved: a length of 30mm, a width of 13mm, a thickness of roughly 1.24mm, and 37.5 and 50mm in between the inner and outer rolls respectively.

The goal of this test is to determine the curved beam strength (CBS). The CBS can be calculated using

$$CBS = \frac{M}{w} = \left( \frac{F}{2 \cdot w \cdot \cos(\phi)} \right) \cdot \left( \frac{d_x}{\cos(\phi)} + (D + t) \cdot \tan(\phi) \right)$$

(2)

where M denotes the moment, w the width of the specimen, F the total force, \(\phi\) the angle, D is the diameter of the cylindrical loading bars, t is the thickness of the sample and \(d_x\) denotes the distance in x-direction between the upper and lower bar. These dimensions are shown schematically in Figure 15. The angle \(\phi\) changes during the test, and can at any moment be calculated using:

$$\phi = \text{Arcsin} \left( \frac{-d_x \cdot (D + t) + d_y \cdot \sqrt{d_x^2 + d_y^2 - D^2 - 2 \cdot D \cdot t}}{d_y^2} \right)$$

(3)

where \(d_y\) denotes the distance in y-direction between the inner and outer roller. This can be calculated using

$$d_y = d_x \cdot \tan(\phi_0) + \frac{D + t}{\cos(\phi_0)} - \Delta$$

(4)

where the subscript 0 denotes the initial angle (i.e., at the start of the test), and \(\Delta\) denotes the displacement in y-direction of the rollers.
From the CBS, the radial stress in a curved beam segment can be calculated using the method originally proposed by Lekhnitskii.\textsuperscript{26} This has the advantage that the result is no longer dependent on the thickness of the sample, and results can be easier compared to each other. The stress in radial direction can be calculated using

\[
\sigma_r = -\frac{\text{CBS}}{r_o^2 \cdot g} \left( 1 - \frac{1 - \rho^{\kappa+1}}{1 - \rho^{2\kappa}} \left( \frac{r_m}{r_o} \right)^{\kappa-1} - \frac{1 - \rho^{\kappa-1}}{1 - \rho^{2\kappa}} \rho^{\kappa+1} \left( \frac{r_o}{r_m} \right)^{\kappa+1} \right)
\]  
\text{(5)}

where \(r_o\) denotes the outer radius of the test specimen. The other terms are defined as:

\[
g = \frac{1 - \rho^2}{2} - \frac{\kappa}{\kappa+1} \cdot \left( 1 - \rho^{\kappa+1} \right)^2 - \frac{\kappa \rho^2}{\kappa - 1} \cdot \left( 1 - \rho^{\kappa+1} \right)^2
\]  
\text{(6)}

\[
\kappa = \sqrt{\frac{E_{\theta}}{E_r}}
\]  
\text{(7)}

\[
\rho = \frac{r_1}{r_o}
\]  
\text{(8)}

\[
r_m = \left( \frac{(1 - \rho^{\kappa-1}) \cdot (\kappa + 1) \cdot (\rho r_o)^{\kappa+1}}{(1 - \rho^{\kappa-1}) (\kappa - 1) r_o^{\kappa+1}} \right)^{\frac{1}{\kappa}}
\]  
\text{(9)}

where \(E_{\theta}\) is the \(E_{11}\) modulus and \(E_r\) can be assumed to be equal to \(E_{22}\).

![Figure 15. Schematic side view of the 4-point bend test according to ASTM D 6415.](image)

Two sets of test results are obtained: one using Suprem material in the layup of \([90/45/-45/0]_s\), one using the Toho Tenax material with an 8-layer uni-directional lay-up. The material data can be found in Table 2. The dimensions measured before the test are shown in Table 3 for the Suprem material, and in Table 4 for the Toho Tenax material. In these tables, 1 denotes the thickness or width at the bottom of the left leg, 2 in the corner, and 3 the bottom of the right leg. The first observation is that the thickness in the radius is smaller than in the legs of the sample, for both materials. This could indicate that during the rotation of the mold, the roller applies more pressure, or because of the slower speed, the roller is here for longer and spreads out the fibres more. The bigger difference for the Suprem material can be attributed to the resin-rich film on the edge of the tows, as observed in companion work by Clancy et al.\textsuperscript{27} This resin could be squeezed out by the roller, causing the thickness to decrease in these regions. The width is relatively accurate: there are no significant differences between the three measurements, and an average can be used.

When doing the test using the Suprem material, some small initial delaminations could be observed in the first 4 samples, as reflected in the results, shown in Figure 18: the stiffness of sample 5 is clearly higher. The results are not as anticipated: it is expected that after the first drop in load, the same load is not reached again. However, in the current results the load increases again after the initial drop in load. The test was stopped when 5\(\text{mm}\) displacement was reached: at this point the sample was nearly flat and the
force measured no longer depends only on the strength in the corner, as can be seen in Figure 16. Since the sample is almost straight, the radial stress calculated is not accurate: the assumption it is part of a cylinder is probably no longer valid.

The maximum load occurs just before the biggest drop just after 4 mm displacement has been applied. This is at almost the same displacement for 4 samples, as can be seen in Figure 18. Sample 4 reaches almost the same load earlier, which leads to a higher CBS and radial stress, hence this is used in table 5. Only sample 2 has no clear drop in load at any point. This result could indicate that the delamination was already present and no new delaminations appeared during the test. A clear delamination can be seen in Figure 17 at the end of the test. Since no big drop in load can be seen, this delamination was already present before the test, which is confirmed by checking the pre-test pictures. The maximal load for this sample is taken before the largest load drop, which is relatively low. The maximally achieved load, the resulting CBS and radial stress are shown in Table 5.

When performing the test with the Toho material, the results were different, as can be seen in Figure 20. During testing a cracking noise was heard, but no associated drop in load was observed. However, the stiffness does change at this point which is indicative of a delamination or buckling event. Some small load drops can be seen, but nothing to indicate a major loss in load carrying capacity. At the end of the test, the sample is completely straight, with a lot of delaminations, as can be seen in Figure 19. As such, buckling appears to have occurred rather than delaminations.

Only sample 1 is shown, but all samples look similar: the delaminations are not symmetric around the corner, and resemble a buckled sample. A possible reason is that the roller is decelerating before, and accelerating after the corner. During the deceleration the laser may power down too late, causing the fibres to be burnt. During the acceleration the laser has to power up, which means a small part of the fibres may
not be sufficiently hot to melt and bond to the substrate. After careful study of the samples, buckling was determined to always occur in the part after the corner. This result indicates the bond in this part is not sufficient, which may be due to the material not being hot enough to reach an optimal bond strength.

To calculate the CBS and radial stress, the load at which the stiffness changes was used. The results can be found in Table 6. Observing these results, it is noted that the radial stress is on average higher than when using the Suprem material. It is to be noted that in the case of the Toho material, the assumptions to calculate the radial stress have been met more closely. The angle is still fairly small, however, given the small size of the sample, the displacement is no longer small. Hence, even for the Toho material, the radial stress is only an approximation. Better results could have been achieved by selecting a different calculation point on the curve, for example, if for sample 6 the small drop at a displacement of 3.67mm with a load of
Table 5. Overview of the results of Suprem material test.

<table>
<thead>
<tr>
<th>sample number</th>
<th>max force [N]</th>
<th>displacement at maximum force [mm]</th>
<th>CBS [Nmm/mm]</th>
<th>radial stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>145</td>
<td>4.26</td>
<td>64.6</td>
<td>17.6</td>
</tr>
<tr>
<td>2</td>
<td>139</td>
<td>4.41</td>
<td>60.3</td>
<td>16.1</td>
</tr>
<tr>
<td>3</td>
<td>171</td>
<td>4.34</td>
<td>64.8</td>
<td>17.4</td>
</tr>
<tr>
<td>4</td>
<td>117</td>
<td>3.19</td>
<td>53.2</td>
<td>13.0</td>
</tr>
<tr>
<td>5</td>
<td>217</td>
<td>4.39</td>
<td>80.5</td>
<td>22.1</td>
</tr>
</tbody>
</table>

Figure 18. Results for 4-point bend test using the Suprem material.

Figure 19. Sample 1 with Toho material at end of test.
322N, the radial stress is found to be 27.1MPa. This is a better result, but is not tabulated and used as an indicator of quality since the drop in load is considered too small to be significant.

### Table 6. Overview of the results of Toho material test.

<table>
<thead>
<tr>
<th>sample number</th>
<th>max force [N]</th>
<th>displacement at maximum force [mm]</th>
<th>CBS [N/mm/mm]</th>
<th>radial stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>122</td>
<td>1.12</td>
<td>74.1</td>
<td>15.1</td>
</tr>
<tr>
<td>2</td>
<td>133</td>
<td>1.20</td>
<td>78.8</td>
<td>16.2</td>
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<td>135</td>
<td>1.11</td>
<td>82.1</td>
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<td>166</td>
<td>1.41</td>
<td>96.1</td>
<td>19.1</td>
</tr>
<tr>
<td>5</td>
<td>187</td>
<td>1.67</td>
<td>105.6</td>
<td>20.2</td>
</tr>
<tr>
<td>6</td>
<td>216</td>
<td>1.66</td>
<td>120.9</td>
<td>24.0</td>
</tr>
</tbody>
</table>

When compared to literature, the radial stress is used since this is usually found to be independent of the thickness.\textsuperscript{28, 29} Only one paper was found where a clear difference in radial stress for samples with different thickness was found.\textsuperscript{30} It is difficult to directly compare the results since no results for the same material, or any other CFRP thermoplastic for that matter, were found. Using a thermoplastic matrix and short carbon fibres, a maximum radial stress of 21MPa was found for a thickness of 2mm and a radius of 3 or 5mm. For a larger radius, the maximum radial stress decreased to 12MPa.\textsuperscript{31}

When looking at thermoset materials, the maximal radial stress found is usually in the range of 27 to 36MPa.\textsuperscript{28, 29, 32} A value of 36 – 40MPa was found for a whole range of thicknesses (4, 8, and 12mm), and a radius equal to the thickness, independent of the lay-up.\textsuperscript{28} Another study found that for 3 and 6mm thick specimens with a radius being either 3 or 6mm, the maximum radial stress was around 30MPa.\textsuperscript{29} While Redman et al.\textsuperscript{32} found found 27 – 28MPa as maximum radial stress for a 3mm thick specimen. The only study that finds a significantly lower radial stress is done for thick laminates: 20, 40 and 60 plies are used, with a radius to thickness ratio of 0.8, 1 and 1.5.\textsuperscript{30} The maximal radial stress is 7 – 8MPa for the thinnest material and only 4 – 5MPa for the thickest laminate. However, this could be due to the increasing radius as well.

When comparing the present results to these, it is noticed that the values are only half of what most thermoset materials reach, but this could be for multiple reasons. Firstly, in the dimensions of the samples: they were smaller than required by the test standard, the radius-to-thickness ratio was large (around 3), and the angle at the start was only 78° rather than 90°. Secondly, the test set-up: the rollers were close to each other, and the upper rollers were close to the tested corner, which can both influence the measurements.\textsuperscript{28}
Thirdly, the way the samples were extracted: for the Suprem samples some delaminations could be seen before the test, as evidenced by a different initial experimental stiffness. Finally, as already mentioned, the assumptions used to calculate the radial stress may not have been satisfied, meaning the stress is more approximate.

For the UD Toho samples, one more reason for the difference can be found: the load and displacement that are used. At this point no load drop is present, but the stiffness changes. A similar result was obtained for woven composites. In this case the reason for the lack of load drop was attributed to the cracks unable to grow due to the woven architecture. Such a process is not happening in our case: all plies are in the same direction and delaminations are observed at the end of the test. However, the ability to retain load carrying capability after delaminations occur is a good sign for the overall performance of the stiffener.

Concluding, the results found using the ASTM-6415 standard are difficult to interpret with confidence. The maximal radial stress found is not as high as in comparable studies, but for this study thermoplastic was used rather than thermostet. Furthermore the samples were small, meaning the rollers were close to the test section and close to each other, the initial angle was not 90°, and the way the samples were extracted leads to initial delaminations. To accurately compare the LATP manufactured thermoplastic specimen results with those presented in the literature, samples of the dimensions according to the test standard need to be manufactured, possibly using the wingbox mold, described in companion work by Oliveri et al. In this way it can be determined whether the LATP process produces parts of acceptable quality. The current samples differ too much from the standard to draw final conclusions, however, the results are considered reasonably good.

VIII. Conclusion

A novel manufacturing approach using winding and laser-assisted automated tape placement for an omega-stiffener manufactured from thermoplastic material has been discussed. The stringer design is used as the stiffening elements in a wingbox. The sizing of the stringer is based on the optimized buckling response of the wingbox, with manufacturing constraints also taken into consideration. The new mold design leads to stiffeners of the correct dimensions in a repeatable manner.

Tests have shown that the bond strength is satisfactory. The strength of the corners was found to be slightly lower compared to the literature for thermostet material. However, the test was not performed according to the standard as the specimen dimensions had to be reduced due to the size constraints of the stiffener from which they were harvested. Future work includes performing tests on samples of the appropriate dimensions that are manufactured using the same manufacturing method to determine the quality of the corners produced using an optimized LATP process.

IX. Acknowledgements

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References
