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Automated fiber placement: The impact of manufacturing constraints on achieving structural property targets for CFRP-stiffeners

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Abstract

The use of automated fiber placement (AFP) to manufacture integrated CFRP stiffening structures leads to a conflict between structural requirements and process limitations in early design stages. In order to avoid costly design iterations, the presented analytical approach enables the computation of tool geometries that are at the limit of theoretical manufacturability. The model is able to determine the profile of manufacturable omega stiffeners with high accuracy. It is shown that the maximum manufacturable profile parameters depend non-linearly on the properties of the AFP system and the profile itself. This allows prioritization of the profile parameters for the efficient definition of omega stiffeners that should meet distinct structural property targets. The results show that current, non-optimized AFP systems already have the potential to manufacture omega stiffeners with sufficiently high stiffness values when taking into account current aerospace applications.

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Keywords: Automated fiber placement; Composite manufacturing; Composite design; Additive manufacturing

1. Introduction

Automated fiber placement (AFP) is one of the established manufacturing technologies for the automated production of lightweight composite structures. It is currently used in aircraft production primarily for large, gently curved components made of carbon fiber-reinforced plastic (CFRP), such as the fuselage shell on the Airbus A350 or Boeing 787 [1,2]. As the technology is getting more refined and less cost-intensive, its potential to move from these simple geometries to more complex, doubly curved 3D structures is being exploited [2-4]. However, AFP poses challenges for design engineers due to unknown process limitations. Limitations regarding the tool geometry and design for manufacturability are not prevalent in literature [5,6]. Brasington et al. [5] note that knowledge about collision avoidance can be obtained by manufacturing experience or extensive simulations and dry runs on curved geometries. This is resource-intensive for design iterations, e.g., optimizing load-bearing structures like stiffening structures. An analytical approach can uncover AFP's potential while avoiding trial-and-error investigations. Furthermore, it could be advantageous to integrate stiffening structures in the fuselage shell already made with AFP, a subject of ongoing investigations in the DFG project OptiFee. To enable an effective evaluation of manufacturability in early design stages, this contribution presents an analytical model with a typical aircraft fuselage stiffener as a use case. The model is then used to find the appropriate geometry of the omega stiffener, which is both manufacturable with a given AFP system and meets structural property targets.

2. Method

As stiffening structures, omega stiffeners (Section 2.1) usually have narrow top and bottom radii to obtain high structural integrity while maintaining small overall

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dimensions for weight savings. AFP, on the other hand, tends to favour shallow curvatures and smooth transitions. To find the overlap between both conditions, the interactions between the geometric parameters of the omega stiffener, its structural property targets (Section 2.2) and the features of the AFP system are analysed (Section 2.3) and implemented in an analytical model. The model is described and validated in Section 2.4.

2.1. Omega-type stiffener

Omega stiffeners (also called "hat stiffeners") are commonly used in composite aerospace construction because they are more convenient to manufacture compared to other types of stiffeners when made from CFRP [1,3,7]. The layup can be done from one side using a single, removable tool [1]. The profile shape of the omega stiffener is characterized by eight parameters (Fig. 1). All parameters except the profile thickness describe the tool surface geometry of the omega stiffener profile, which is the first ply of fibers when manufactured with AFP. The profile thickness determines the surface geometry of the stiffener or the topmost ply. A larger profile thickness implies a smaller bottom radius and a larger head radius for the surface of the profile, considering an unchanged tool geometry. When determining the geometrical manufacturability of the male side of the omega stiffener, the minimum convex radius is therefore to be measured at the inside or bottom layer of the omega profile, while the minimum concave radius is on the surface layer. An important point for the following investigations is the bottom inflection point, where the bottom curvature ends and transitions into the web of the stiffener. The web of the stiffener connects the bottom radius with the top radius (a). For larger values, the foot and head radii can merge directly into one another (b). In this case, there is no flat web and the web angle is equal to the angle of the profile at the inflection point.

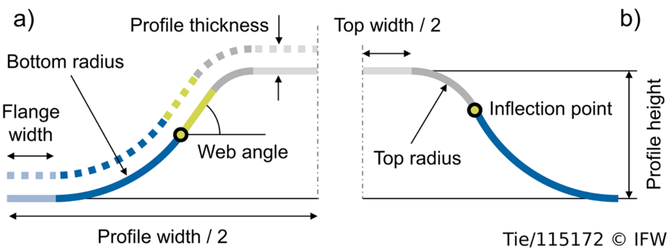

Fig. 1. Parametric profile of an omega stiffener depicting each parameter.

2.2. Definition of structural property targets for omega stiffeners

In order to assess whether an omega profile is suited for an aircraft application solely based on the profile geometry, target values in the form of area moments are defined. The moments of area are well suited for this as they express the main influence on important stiffness parameters of a stiffener. Structural stability, although also largely influenced by the profile geometry, is not considered in detail. Only the maximum profile width of 150 mm is set as a stability constraint. The target values for the second moments of area are derived from typical profiles used in single-aisle aircraft. Profile sizes are taken from literature and the respective moments of area are calculated. Typical values are listed by Dickson et al. [8] for I-profiles and by Mikulik et al. [9] for omega and Z-profiles. The resulting overall minimum and maximum values for I_y and I_z are listed in Table 1. Since the problem in manufacturing with AFP is to achieve larger dimensions in the z-direction, in the following, the values for I_y are taken as the main target parameters. The I_z target values were achieved by all profiles examined.

Table 1. Structural property targets based on typical aircraft profiles.

Target Parameter	Minimum Value	Maximum Value
$I_y\,[mm^4]$	4.500	2.700.000
$I_z[mm^4]$	3.000	800.000

2.3. Process limitations of the AFP system regarding CFRP omega stiffeners

Regarding process limitations of the AFP technology, there is a hard limit to some extent between what is theoretically and impossibly manufacturable and soft limits such as economic or qualitative factors within a given production system. Approaching the theoretical limits, it is usually the case that quality becomes unacceptable. Therefore, it is important to note that manufacturability in this contribution does not imply that it would be possible to produce a viable part. In the remainder of this paper, focus will be put on the geometrical or theoretical process limitations of AFP, disregarding the economic and qualitative aspects of manufacturability.

In general, an AFP-manufacturable geometry is constrained by the AFP system in three aspects. The AFP system has to be able to deposit the tape following the layup path at any point during the process, the tape has to be able to describe the layup path sufficiently and, at any point, the AFP system must not intersect the geometry. Because the cylindrical compaction roller has to keep contact with the tool surface throughout the layup process, AFP-manufacturable geometries can be most likely described as a smooth surface without sharp edges or discontinuities. Consequently, the surface is continuous and hence infinitely differentiable, which allows its approximation with curvatures or radii. This can be used as a basis to establish a correlation between the features of the geometry and the features of the AFP system, for example in an analytical model. The task of this model could be: what curvatures can a given AFP system in any direction handle? Thus, the omega stiffener is an apt example geometry because of its simple open surface with an alternating constant convex and concave curvature in a single direction. The geometry of an omega stiffener manufacturable with AFP is dependent on different features of the given AFP system as well as the laminate structure of the CFRP laminate as a design parameter. The four main features of the AFP system are layup material, geometry of the layup head, compaction roller and geometry and range of the actuator. These features influence the profile of the omega stiffener in different ways, summarized in Table 2. In the following, the geometry of the actuator and its range are neglected, as this is mostly an individual problem of correct setup and programming. The minimal bottom radius is determined by the material (properties, flexibility, fracture strain), geometry of the layup head (risk of collision) and its compaction roller geometry and properties (number of segments, material, travel). As there is no risk of collision for isolated convex curvatures, the top radius is only defined by the compaction roller properties and the material. The maximal web angle and the profile thickness are both dependent on the geometry of the layup head. Neither the profile height and width, nor the top width and flange width of the omega stiffener are impacted by the AFP system. In the present investigation, the width is chosen as a restricted value, while the height is a target value. A further consideration is the layer structure of the laminate, which determines the varying directions of the placement. This means that an AFP system can manufacture completely different geometries in one specific direction, e.g., along the stiffener, than in another, e.g., across the stiffener. The laminate structure as a design parameter therefore has a separate influence on the profile shape.

Table 2. Interdependence between the considered AFP system features, omega stiffener parameters and design parameters.

Omega stiffener parameter	AFP system features	Design parameter
Profile height	-	-
Profile width	-	-
Bottom radius	Layup material Geometry of the layup head Compaction roller	Ply angles
Top radius	Layup material Compaction roller	Ply angles
Web angle	Geometry of the layup head	Ply angles
Top width	-	-
Flange width	-	-
Profile thickness	Geometry of the layup head	Ply angles

2.4. Analytic process limitations model

An analytic model written in Python is introduced and validated to connect the features of the geometry to the features of the AFP system. The results of the model are output in radii and gradients, allowing conclusions to be drawn about the manufacturable geometry.

2.4.1. Layup material

The layup material is a generic unidirectional slit-tape thermoset prepreg with a tow width of ¼”. The drape of most thermosetting resins under process temperatures results in a low stiffness in y- and z-direction. This, combined with the high tack, allows the material to be draped on small curvature radii < 5 mm out-of-plane in and perpendicular to the feed direction. The minimum layup radii for concave and convex curvatures are therefore determined by the other properties of the AFP system and the minimum manufacturable concave and convex radii due to the layup material are conservatively implemented as a constant value of 5 mm.

2.4.2. Geometry of the laying head

The shape of the laying head has a major effect on the manufacturable geometry of the work piece, mainly because of the risk of a collision. Protruding components such as heating lamps or tow coils can collide with the tool or work piece, especially if it is concave-shaped or double-curved. For the analytic model, the layup head geometry is implemented as a convex hull. By parallel projecting the 3D convex hull perpendicular to the current layup direction in the x,y-plane, it is possible to determine if the layup head and structure intersect. The process is shown in Figure 2, where the resulting 2D-projection of the laying head is marked with a blue outline. In a 3-step process, the smallest concave radius (Fig. 2, black arc) is calculated for a given inflection point height. The tangent of the radius at the inflection point height (Fig. 2, green line) must not intersect the convex hull and determines therefore the maximum gradient angle. As a result, the minimum convex radius and the maximum gradient angle depend on the height of the inflection point. By default, the laying head is always perpendicular to the surface, but there is also the possibility of a static and dynamic tool tilt. When tool tilt is considered, the 2D projection of the convex hull is rotated around the axis of the compaction roller at the start of the calculation.

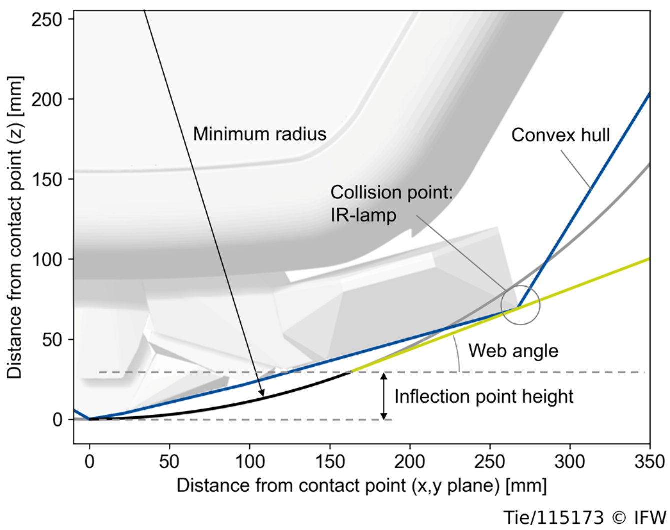

Fig. 2. Representation of the analytic collision analysis with a model of laying head B in the layup direction at an inflection point height of 30 mm.

2.4.3. Compaction roller

Ensuring sufficient consolidation of the tow through the compaction roller is important when assessing the manufacturability of a geometry. Shape, material and composition as well as segmentation and travel of the compaction roller determine the contact between itself, the tow and the layup structure. Considering the compaction roller in isolation, curvatures in the feed direction (x-direction) are determined by the roller diameter and, to some extent, by the composition of the rollers and the material. In the analytic model, this is implemented by setting the

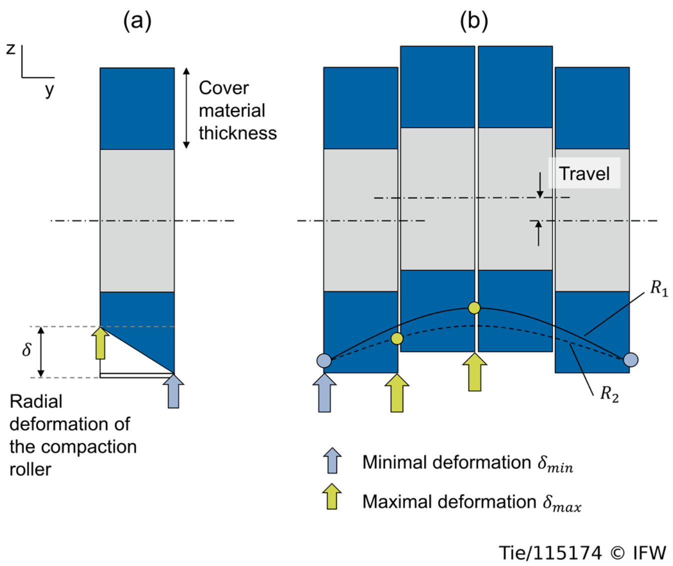

Fig. 3. Representation of the AFP compaction rollers and the calculation of the minimum curvature transverse to the feed direction.

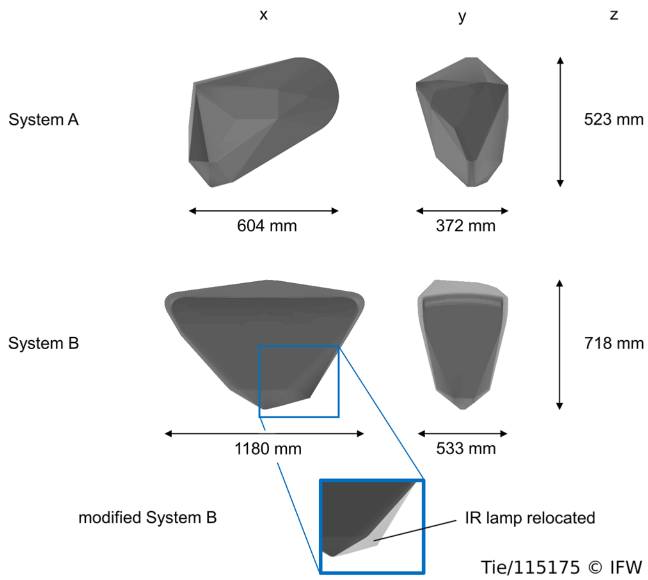

Fig. 4. Convex hull dimensions of the investigated AFP systems.

narrowest possible radius in feed direction as the radius of the compaction roller of the given AFP system. For curvatures transverse to the feed direction (y-direction), the number, width and stroke of the rollers are relevant. In the model, a simplified stress calculation is assumed (Fig. 3). A soft silicone material is chosen for the coating of compaction rollers and it is specified that the material must be radially deformed between 5% and 30% of the coating thickness to ensure sufficient but not excessive consolidation [10]. The minimum radius is defined by the fact that the curve of the geometry must therefore pass in between the maximum or minimum radial deformation $\delta_{min/max}$ at the edges and the center of each roller in order to allow consolidation and to avoid damage to the roller or structure. The stroke of each roller is considered as well. As seen in Figure 3 (b), the curve R_1 would dent the left compaction roller more than the defined maximal radial deformation. Therefore, the curve R_2 is the correct minimal manufacturable radius. Curvatures that are not at a 0° or 90° angle to the direction of travel are projected into its respective parts.

2.4.4. Investigated AFP systems

Table 3 shows the features of the investigated AFP systems A and B, which were processed by the model. The convex hulls are shown in Figure 4. The system "B modified" differs from the default system B only in the relocation of the infrared (IR) heat lamp, i.e., an adapted convex hull.

Table 3. Features of the two investigated AFP systems.

AFP system	A	B
Number of roller segments	1	4
Roller diameter [mm]	39	68
Roller width [mm]	31	6.35
Travel of rollers [mm]	-	4
Thickness of cover material [mm]	9	8

2.4.5. Validation

The model is validated using the commercial AFP path planning and simulation program AddPath. The collision analysis was tested using a ramp geometry consisting of a concave radius transitioning into an infinite ramp at the specified inflection point height. The concave radius is to be minimized. The results of the analytical models were compared with the collision analysis of the simulation for ramp geometries with five different inflection point heights (10 mm, 20 mm, 50 mm, 100 mm, 150 mm) and five ply angles (0°, 30°, 45°, 60°, 90°). Figure 5 displays the results of the concave radii for 0°, 45° and 90° for AFP system B. The overall results show good agreement between analytic model and simulation, with a deviation of between -3% and 4% for convex radii and ±2% for gradient values. Furthermore, nine different omega stiffener profiles with varying profile widths (50 mm, 100 mm, 150 mm) and ply angles ([0/30/-30/90]°, [0/45/-45/90]°, [0/60/-60/90]°), which are considered only just manufacturable by the analytical model, were analyzed with the process simulation for both AFP systems. All of the proposed omega stiffeners were simulated without collision.

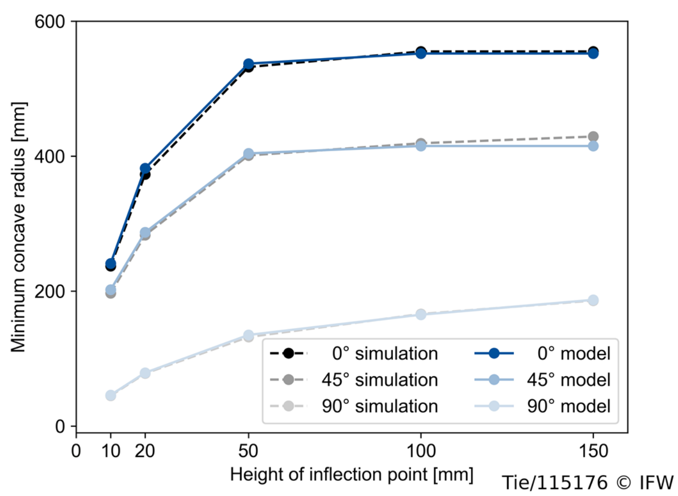

Fig. 3. Validation results of convex radii for AFP system B.

3. Results and discussion

Each profile parameter affects the structural performance of the omega stiffener in a different way depending on the stiffener's initial shape (Section 3.1). Considering this allows to prioritize each parameter for achieving the structural targets. The AFP systems have a nonlinear influence on the manufacturability of individual parameters of the omega stiffener depending on the height of the inflection point (Section 3.2). Section 3.3 discusses the resulting stiffener geometries when manufacturing constraints for given AFP systems and structural property targets are both considered.

3.1. Achieving structural property targets

The impact of each parameter of a given omega stiffener on its second moment of area is displayed in Figure 6. The base profile defined by the base values is shown in Figure 6 (a). The alteration of each parameter from its base value is plotted as a percentage value on the x-axis. The change in any individual parameter, while all others are held constant, causes a change in the second moment of area relative to the base profile. This change is plotted on the y-axis. By analyzing several basic profiles, it is possible to determine what general effects a change in a particular parameter causes in the second moment of area. While the impact of each parameter is highly dependent on the base profile, some tendencies can be identified for profiles likely manufacturable with AFP. Larger second moments of area can be achieved by enlarging the profile width or the profile thickness. If a non-curved web accounts for a large proportion of the surface area of the stiffener, the web angle has a major influence. Increasing second moments of area can also be achieved by reducing the top and bottom radius, as well as reducing the head width. Generally, to achieve higher stiffness, widening the profile proves to be the most efficient method, but it is also often a regulated parameter. In addition, small convex radii can generally be produced well by AFP systems. Therefore, a small bottom radius and a steep web angle are identified as the limiting parameters for AFP systems in achieving structural property targets.

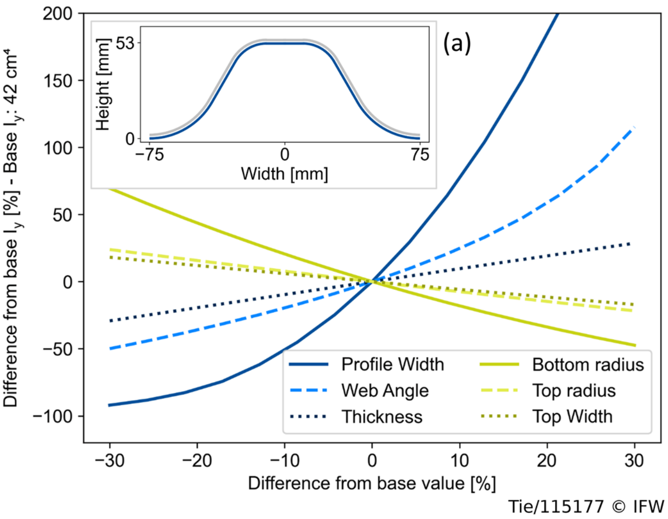

Fig. 6. Percental impact of altering omega profile parameters on second moment of area. Base profile as shown in (a) with bottom ply (blue line) and top ply (grey line): profile width: 150 mm, foot radius: 40 mm, web angle: 60°, top radius 20 mm, profile thickness: 2 mm, top width: 20 mm, resulting height: 52.58 mm.

3.2. AFP manufacturing constraints

The two AFP systems both have a variable impact on the foot radius and web angle in relation to the height of the inflection point, as shown in Figure 5 for system B. When the height of the inflection point is increased, the minimum manufacturable bottom radius increases as well, while the web angle decreases. This is because the layup head becomes wider towards the top and is thus more likely to collide with steep, tall structures. This affects the shape of the omega profiles that are just about manufacturable with an AFP system. Changing the height of the inflection point changes, therefore, not only the bottom radius and web angle, but in turn also the shape and second moment of area of the omega stiffener, if the other profile parameters are non-varying. This means that there must be an inflection point height for which the second moment of area of a profile is at its maximum (Fig. 7). It can be seen that by increasing the inflection point height starting near 0 mm (a), the second moment of area increases until its maximum (b). If the inflection point is increased further, the bottom radius increases too far while the web angle is forced to become shallower (c). At this point, the height of the stiffener is reduced, and at the same time, the second moment of area is reduced again.

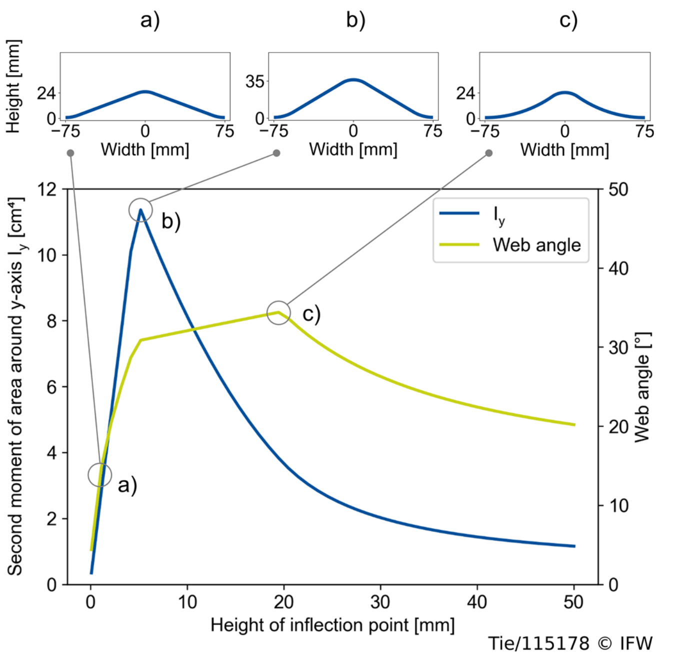

Fig. 7. Omega profile with maximal second moment of area depending on the height of the inflection point (System B modified, profile width: 150 mm, head radius: 20 mm, profile thickness: 1.5 mm, top width: 0 mm).

3.3. Finding the optimal omega stiffener profile

Figure 8 shows the second moment of area of an omega stiffener depending on its profile width and the bottom radius. The other profile parameters are fixed (top radius: 10 mm, maximal web angle: 80°, top width: 0 mm, profile thickness:

4 mm). The area between the minimal and maximal structural target values (0.5–270 cm^4) is colored according to the increasing second moment of area. Two solid, grey lines show the maximal manufacturable omega stiffeners of the two respective AFP systems depending on the bottom radius and the profile width. Omega stiffeners with a higher second moment of area cannot be manufactured with the respective system. Both systems are capable of manufacturing omega stiffeners of varying widths that meet the specified minimum second moment of area. With increasing profile width, the maximum achievable second moment of area increases as well. This is due to the AFP system's ability to layup steeper web angles while maintaining the same radii when manufacturing wider profiles. The dotted line shows the modified system B, where the IR lamp was repositioned. Since the IR lamp is a low-hanging, protruding structure, it has a negative influence on the minimum manufacturable bottom radius. By repositioning the lamp, a higher second moment of area can be achieved, thus extending the limit in terms of achieving structural property targets.

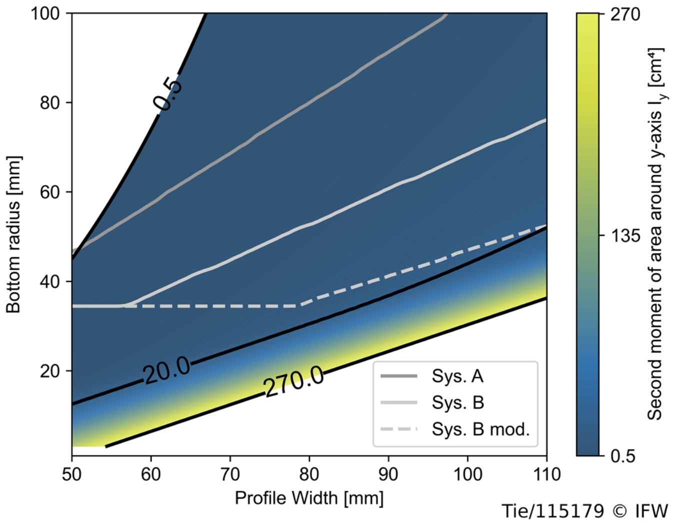

Fig. 4. Second moment of area of maximal manufacturable omega stiffener profiles for different AFP systems.

4. Conclusion

An analytical model to efficiently find optimal geometries for omega stiffeners in early design stages, taking into account both their structural property targets and theoretical manufacturability, is presented. It is validated with process and collision simulations and shows high accuracy. In the investigations, it is pointed out that the individual omega profile parameters have varying effects on the second moment of area, with the profile width and bottom radius standing out. Furthermore, correlations between the individual parameters and the features of AFP systems have shown that the bottom radius and the web angle are important parameters in achieving high stiffness values for omega stiffeners manufactured with AFP. It turned out that these two parameters are not constant for the examined AFP systems but are dependent on the height of the inflection point. Knowing these characteristics allows to find an omega profile with a maximized second moment of area for a predefined width. Consequently, the analytical approach is able to prioritize the influence of process and geometry parameters to effectively find a trade-off between manufacturability and structural performance. The results show that current non-optimized AFP systems already have the potential to produce omega stiffeners with sufficiently high stiffness values when taking into account current aerospace applications. Furthermore, it can be concluded that by manipulating today's AFP laying heads, the complexity of theoretically feasible geometries can be increased. Looking ahead, the model can be used for more detailed considerations regarding AFP layup head design and will be integrated into an integrated design methodology to assess the manufacturability of unconventional stiffening layouts.

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Contributions

Conceptualization: T.T., L.R. and C.S; methodology: T.T.; formal analysis: T.T., L.R.; data curation: T.T.; visualization: T.T.; writing – original draft: T.T., L.R.; writing – review & editing: C.S., B.D., P.H., S.H.; supervision: C.S., B.D., P.H., S.H.; project administration: B.D., P.H., S.H.; funding acquisition: B.D., P.H., C.S.

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