FABRICATION OF COMPOSITE CYLINDERS WITH INTEGRATED LATTICE STRUCTURE USING FILAMENT WINDING

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Abstract

Composite lattice structures present favourable stiffness-to- and strength-to-weight overall ratios allowing for significant weight reductions and material savings. Within the WASIS project, a wafer-like integrative approach was considered for an innovative aircraft fuselage, in which a patterned network of stiffening ribs and the cylinder skin are jointly manufactured. A cylindrical fuselage section was designed and its manufacturing was herewith implemented through filament winding. A step-wise approach was used to gradually develop and dominate the increasingly complex tools, process kinematics and control for accurate prototype manufacturing, as shown hereafter. Feasibility analysis is also addressed in the paper.

1. Introduction

Composite lattice structures are being gradually re-introduced into aerospace and aeronautic applications. Their favourable stiffness-to- and strength-to-weight overall ratios allow for significant weight reductions and material savings, thus enforcing their attractiveness. Within the scope of the WASIS project, a wafer-like integrative approach was considered in which a patterned network of stiffening ribs and the cylinder skin are jointly manufactured. Such integral composite structure avoids additional interface and/or joining elements between the structural ribs and the skin, as well as in the crossing points of the ribs.

Although the main advantages of this structural organization seem clear, the limited studies conducted by other authors in the past were based on idealized and/or coupon like test specimens [1], addressing only virtual modelling [2][3][4][5] or focused in very limited number of parts/prototypes [6][7], thus not focusing on the manufacturability as main concern. Therefore, both the structural ability and the manufacturability were not fully assessed, since the continuity of the long fibres and the practical issues related to the real manufacturing process were not accounted in. Nevertheless, a few studies were effectively conducted on the manufacturability of composite lattice structures, either focusing on non-curved grids [8][9], in non-productive manufacturing processes, like tape placement techniques [10] or on dedicated filament winding (FW) applications [11][12][13][14] as is the focus of the present paper. Due to its high productivity, continuous nature and applicability to the designed geometry, the FW technique was selected and implemented for the required prototypes. The FW manufacturing of such cylindrical self-ribbed structures poses several practical challenges that were experienced by these authors [11][12][13][14]. However, to our knowledge, none has tested nor provided a solution for interconnectivity between several wound cylinders, to be placed in adjacent positions in the overall structural to which they borrow strength. This specific challenge was addressed in the WASIS project and consists of the main progress beyond the state of the art. Progressive developments and setup implementations were done in view of solving and adding complexity in a step-wise approach.

Firstly, the kinematic parameters of the manufacturing sequence were studied and adaptations of the structural concept were imposed for the sake of feasibility. Namely, the minimum distances between the physical connectors to be placed at the edges of the cylindrical sections as well as their geometry were established. Specific and complex tools were designed and setup to assist the fabrication of the required wafer-like structures. Progress in manufacturability studies was made from winding small representative details of the complex structure (crossing points and connector points), then curved panels and finally the complete cylinders. In this way, the feasibility and the required know-how to produce such complex composite structures were gathered steadily. This allowed assessing also the macroscopic quality of the components fabricated.

In this paper the limitations in the manufacturing of composite structures with integrated lattice structure through FW are discussed together with the challenges overcome and results of the extensive winding trials conducted. Features such as the accommodation of the fibres, crossing points, interface attachments and physical restrictions are specifically addressed in view of giving an insight to the effective potential of this technology. The suitability of a cost-effective way to fabricate such complex structures, including smaller local details needed to fulfil the “building-block approach” for development was demonstrated. This paper is also complemented by those presented by other project partners, namely focused in the design guidelines and/or the testing of the complex structures produced.

2. Manufacturability Studies

In the early stage of the manufacturing setup, several feasibility studies were conducted at specific critical spots. These are schematically indicated in Figure 1.

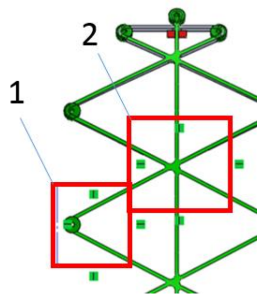

Figure 1 – Identification of the critical spots for early feasibility studies.

2.1. Turn-around zones

Composite lattice structures are clearly benefited if composed by continuous fibres. In order to guarantee such fibre continuity, pins or inserts (hereafter called reels) are needed in the end of the segments, allowing continuous turn-around and uninterrupted winding operation without cutting of fibres (see Figure 2).

In WASIS project the pins to guarantee fibre continuity have simultaneously the purpose of transmitting loads between the composite and the main interface elements to the adjacent cylinders. To validate reels geometry some tests were performed to validate minimal distance between consecutive reels (pins clearance for FW delivery head) as well as the reel geometry itself (minimum allowable radii to avoid fibre excessive curvature and potential breaking at winding). Regarding reel geometry there are three other major aspects to account in: (i) the minimal distance between the planar washers that allows reliable positioning of the fibre tows inside the “groove”, (ii) the contact area between the reel (metallic) and the fibre that concurs to the required additional shear strength to withstand the project loads and (iii) the washers’ edge geometry to avoid fibre cutting.

Figure 2 – Views of reels at the ribs turn-around zones.

2.2. Ribs’ cross points

Due to the overall pattern of the lattice, there are ribs crossing points in which two or more ribs intersect each other, thus creating undesired local over-thickness phenomena. In this particular case the developed lattice structure also have hoop ribs intersecting with the helical ones which further emphasizes the complexity of each “triple” crossing point. At beginning, no evidence was available of up to what extent the fibres would be compacted by the FW radially inwards pressing mechanism at the crossing points and if such mechanism would be suficcient to accommodate the excess fibres into the available grooves.

One first minimization of the problem was achieved by agreeing with designers to move the hoop rib (the third one crossing) away from the exact crossing point of the helical ribs. Still, there was a need to demonstrate the accommodation of the fibres in this critical spot.

Three different winding paths were tested and are schematically represented in Figure 3. These alternative paths promote considerably different through-thickness profiles at the crossing points, since they distribute the fibre tows in quite different manners in each passage. This preliminarily showed us that the accuracy of fibres positioning onto the reference tool and the correct choice of the winding kinematics would promote completely different results for the final structure.

A specific mould was designed and implemented for the winding trials of the crossing point solely. In the final configuration, the grooved crossing zone was made with rounded corners, thus creating greater accommodation space for the fibres. This, on the other hand, set the assumption that the fibres would not be “straight” but rather locally misaligned to fill the available additional space. This was agreed and decided in order to favour continuity of fibres and reasonable level of local over-thickness.

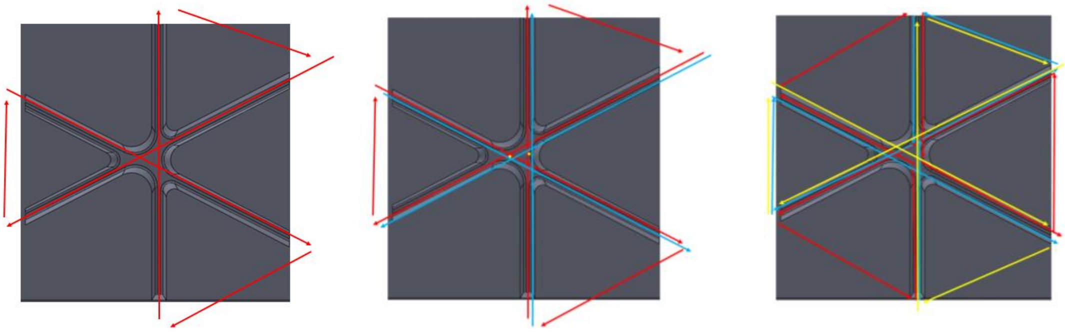

Figure 3 – Direct fibre path (left), direct fibre path with diverging pins (centre) and indirect path (right).

3. Fabrication of Prototypes

3.1. Attachment Frame Connection Detail

In order to have a first realistic winding manufacturability assessment of the wafer-like structure, INEGI prepared and fabricated a level 2 local detail that included (i) one reel, (ii) the attachment frame and (iii) the ribs and skin interfaces. These sub-elements incorporate most of the complex aspects of the final prototypes: (i) turn-around winding placing the fibres onto specific washer spaces as the ribs builds-up, (ii) intermediate step for assembling of the attachment frame detail and the mould extensions, (iii) the ±45º skin layers with complex edge configurations to save material and (iv) the de-moulding issues. To fabricate this attachment frame detail a non-axisymmetric modular steel mandrel was designed and setup in order to allow the joint incorporation of:

- the negative part of the ribs that will give the ribs final shape;
- support the reel prior to frame attachment (while winding only ribs);
- support the attachment frame upon conclusion of the ribs ans transition to skin winding;
- curved extensions for extra skin winding.

To manufacture the negative part of the ribs three different moulding materials were tested in order to comply with manufacturing, curing and post-curing, costs, geometrical stability and de-mouldability requirements. The selected material was an aluminium-charged epoxy resin.

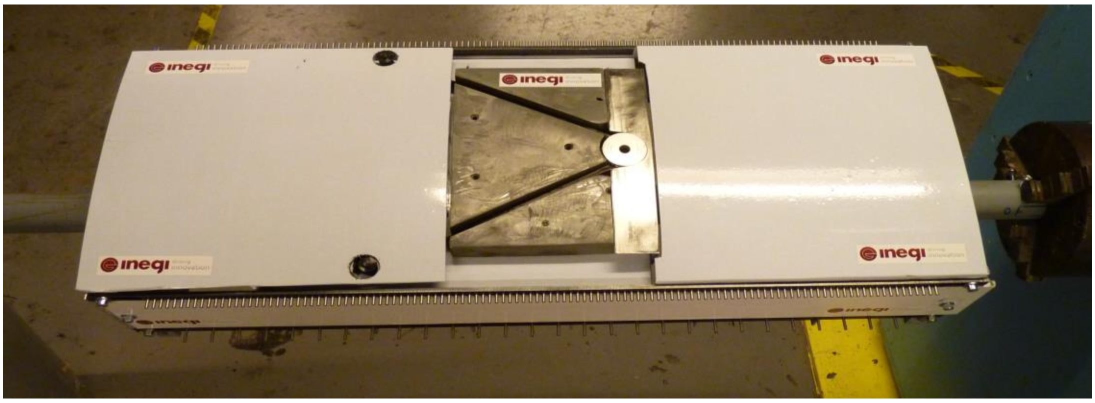

Figure 4 – Attachment frame connector detail mandrel.

Figure 5 – Attachment frame connector details without skin (left) and with skin (right).

One specific challenge that was first observed was related with the trapezoidal cross-section of the ribs. This implied that increasingly more fibre tows needed to be placed in the several washer grooves as the stack buids-up. This was resolved by progressively imposed greater number of winding cycles as the ribs built from inner to outer regions.
Skin surface finishing was another critical issue to be analysed and solved due to the slight indentations created by the ribs contact with. Such interference between ribs and skin is desired to promote proper adhesion. On the other hand, correct winding tension must be provided in order to allow for enough and homogeneous compactions of the skin laminate.

3.2. Full-Scale Regular Test Panel

The next step in the “building block approach” and test plan for the consortium, as well as in degree of complexity, a full-scale test panel was manufactured by INEGI team. The basic mould concept was kept, taking advantage of the previous experience with the detailed spots. The main section of the mandrel was composed of a sliced modular surface composing the external reference geometry for the grooved tool. The reels were precisely positioned and fixed in such a way that they could be released together with the composite panel after de-moulding. Two lateral extensions where then assembled after ribs winding process, to allow proper space for skin build-up.

At this tool development for regular test panel fabrication one of the main concerns was to design a tool that allows manufacturing several parts (permanent tool), in opposition to the wasted mandrels solutions used by other authors [12][13][14]. The major challenge to overcome is the de-moulding operation due to non-compatible drafting angles of the de-moulding surfaces. Our sliced rigid surface approach accomplished this goal (Figure 6).

Several reels positions were defined all around the panel edges, thus further increasing the complexity of (i) the winding program to be developed (additional alternative paths were used due to the top/bottm extra reels turn-around zones), (ii) the ribs thickness homogeneity, (iii) the skin compaction and correct placement at the desired diameter and (iv) the surface finishing with our specially design external compacting element.

The prototype is shown in and represents the penultimate step before the fully cylindrical prototypes.

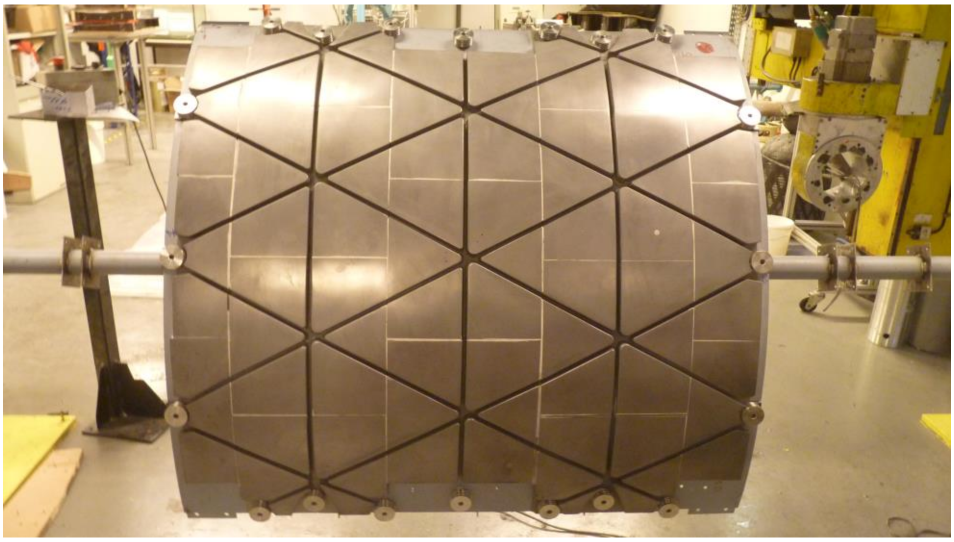

Figure 6 – Full-scale regular test panel sliced rigid mandrel (central section).

Figure 7 – Full-scale regular test panel prototype.

3.3. Small-Scale Cylinders

For the cylinder prototypes, so-called barrel prototypes, the previous know-how gathered from the small details up to the test panel was of essence. Two tooling approaches were followed: (i) non-permanent (lost) mandrel surface by CIRCOMP and (ii) permanent mandrel tool by INEGI. The following pictures show the tools and prototypes that substantiate the main results of the WASIS project.

The non-permanent tool allowed a fsater and more affordable development and finalization of a single prototype. Such prototype was further tested by other WASIS partners and results shown elsewhere. On the other hand, the permanent mandrel solution envisaged to demonstrate the future industrial feasibility of the manufacturing of this kind of wafer-like structure in a cost-effective way, whilst using a very controllable and affordable manufacturing process, which is FW.

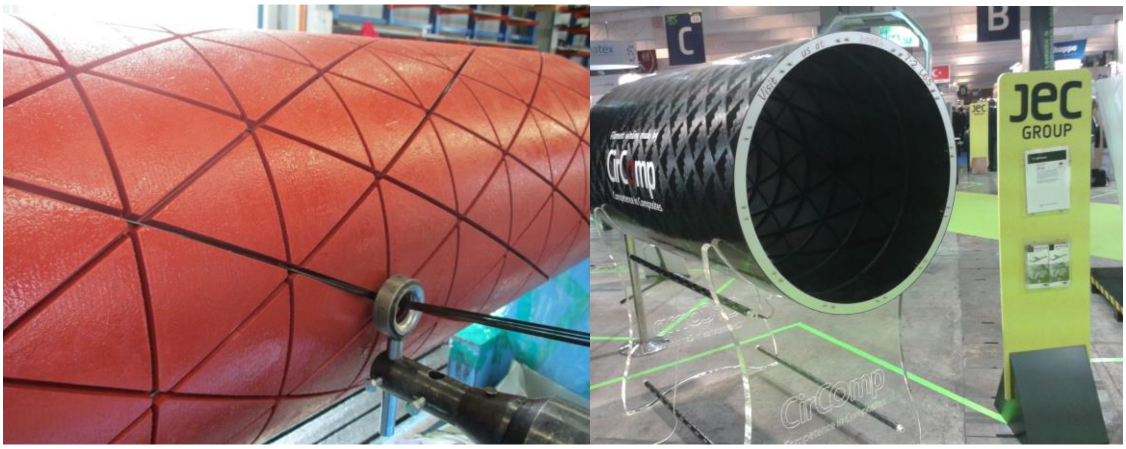

Figure 8 – 1m barrel lost mandrel (left) and final prototype (right).

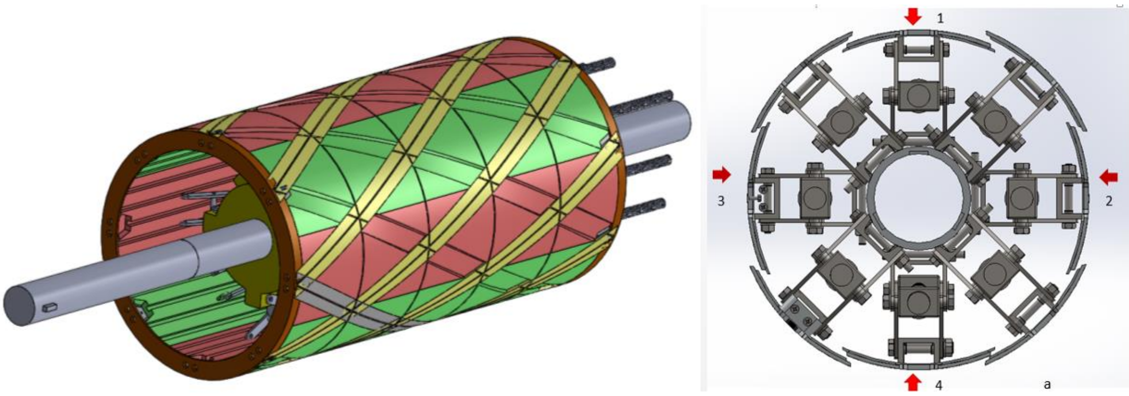

Figure 9 – overviews of the 0.5m barrel permanent mandrel design.

4. Conclusions

For the wide spread use of cylindrical composite lattice structure, namely for aircraft and aerospace applications, some challenges needed to be overcome. One of these was the manufacturing process. At this stage we can claim with some confidence that the proposed approach is applicable to industrial needs. And this was the main purpose of the present study. Despite these preliminary achievements, there is still a long way to go through in order to further validate and secure these technological solutions for aeronautical industry.
Manufacturing process improvements will be addressed in several phases of the upcoming work, in order to gain confidence in critical aspects such as (i) wise fibre trajectories, (ii) improved turnaround efficiency, (ii) decreasing of fibre breakage, (iv) process speed, (v) surface preparation and better adhesion, (vi) optimized crossing points and characteristics, among other. Nonetheless, the proof of concept was successfully achieved and future work will allow to reach even higher TRL solutions, with increased interest to industry and composite engineers in general.

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