MANUFACTURING AND TESTING OF COMPOSITE WAFER COMPONENTS WITH DUAL-PURPOSE INTEGRATED SEMI-LOOP JOINTS

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Abstract

Application of optimal reinforcement concepts like lattice or wafer and increasing of airframe integrity based on conventional mechanical fasteners replacement by high-efficient hybrid metal-to-composite joints provide strong opportunities for airframe structures weight reduction. Within this work full manufacturing process used for production of single curvature CFRP wafer panel with integrated dual-purpose semi-loop hybrid joints is presented along with discussion of panels testing results.

1. Introduction

Efficiency of metal structures and components replacement by composite ones has already been demonstrated by the leading aircraft manufacturing companies. The next promising step in the struggle for further airframe weight reduction is implementation of optimal reinforcement concepts that will allow to realize extreme specific mechanical characteristics of unidirectional composites. In case of aircraft fuselage section that is a closed contour structure working under non-uniform/variable loads, sufficient weight saving could be achieved as a result of lattice or wafer reinforcement realization [1]. This approach provides an opportunity for multi-parametric optimization of target structure design (incl. overall reinforcement scheme, mechanical/geometrical characteristics of skin and ribs, etc.) to ensure minimal weight in parallel with high level of safety. Another strong option for weight saving is increasing of airframe integrity level. It could be achieved as a result of refinement of composite structure joining techniques and replacement of conventional mechanical fasteners by high-efficient hybrid metal-to-composite joints [2]. These joints ensure smooth load transfer from composite structure to the metal one and do not require any additional reinforcement.

Both options were combined in the innovative design of full-composite wafer fuselage section with integrated metal attachment frame that was developed in the frame of EU FP7 WASIS project (www.wasis.eu). Key elements that ensure technical feasibility of this innovative structure are hybrid metal-to-composite semi-loop joints (see at Figure 1) that are used for generation of CFRP wafer structure and ensure its integrity with metal attachment frame without any conventional fasteners application.

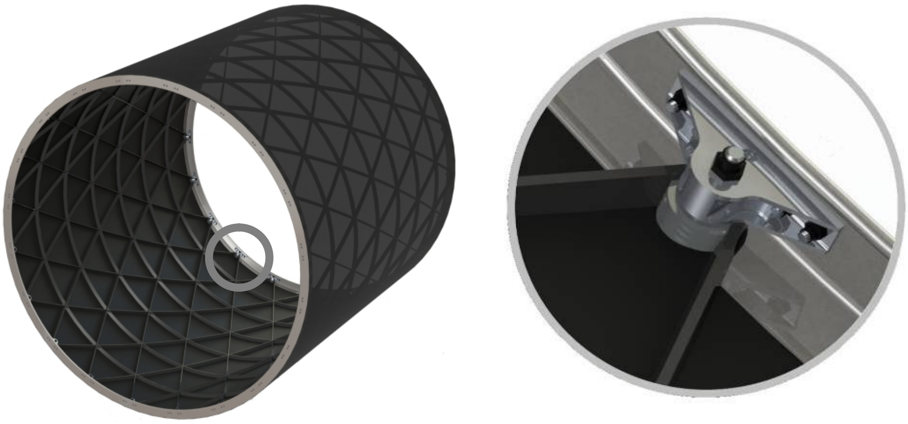


Figure 1. Full-composite wafer fuselage section design with integrated metal attachment frame based on semi-loop joints application

This work was motivated by the necessity to validate new fuselage design in terms of manufacturability as well as experimentally verify analytical and numerical models used in the design. Large full-scale single-curvature wafer panel (with overall dimensions over 1x1 meter) was selected as a representative element to be used for these purposes. To broad the scope of research, manufacturing and testing of regular wafer panel and wafer panel with opening created without reinforcing ribs cutting were realized in parallel.

2. Manufacturing

2.1 General manufacturing process and tooling for integral wafer structures production

Cylindrical shape of full-composite wafer fuselage section (Figure 1) opens the way for application of high productive and cost-efficient filament winding process. However, to ensure high load-carrying capacity of designed wafer fuselage section and its integrity with metal attachment frames, conventional approach for both manufacturing process and tooling was modified to meet the following requirements:

- Continuity of reinforcing lattice structure;
- Integrity of reinforcing lattice structure and attachment frames;
- Reliable joining of reinforcing lattice structure and fuselage skin without any additional joining elements;
- High accuracy of geometrical and mechanical characteristics of wafer structure elements (reinforcing ribs and skin);
- Out-of-Autoclave (OoA) curing of fuselage section without additional pressure;
- One-stage manufacturing process.

To create solid lattice structure and provide its integrity with attachment frames, it was proposed to generate lattice ribs by means of uninterrupted winding of impregnated carbon fibre around the semi-loop joints. These joints are inherent components of attachment frames that have to be installed to the cylindrical metal collapsible mandrel normally used for filament winding of composite structures. To ensure designed cross-section geometry of fuselage ribs and allow further winding of fuselage skin, a novel concept of special shape-generating mould (to be installed to the metal mandrel) was developed. Shape-generating mould represents a solid mould with appropriate system of grooves that corresponds to the lattice structure geometry. Material of shape-generating mould has to ensure tooling dismountability after fuselage section curing because of its high flexibility, on the one hand, and to provide required compaction of ribs and skin in case of OoA curing due to its high coefficient of thermal expansion (CTE), on the other hand. It was shown during the manufacturing process and tooling development phase that the only material that completely meets these requirements is silicone.

Therefore, designed composite wafer fuselage section with embedded metal attachment frames could be produced using above-described combined tooling (metal mandrel + silicone shape-generating mould) [3] with installed attachment frames by means of uninterrupted filament winding of lattice reinforcing structure (due to semi-loop joints application) followed by the skin winding and complete structure curing in OoA mode with vacuum pressure application.

To validate developed manufacturing process and tooling design and to clarify potential difficulties and bottlenecks before the real-scale structures production, pilot manufacturing of wafer test panels was performed as it described below.

2.2 Modified manufacturing process and tooling for wafer test panels production

Following general approach for integral wafer structures production, a "semi-winding" technique was developed and used in manual way to produce lattice structure of wafer test panel. "Semi-winding" technique is pretty close in its nature to the filament winding, because the lattice structure is generated at the tooling of positive curvature as a result of successive winding of impregnated fibre on semi-loop reels that are fixed on the tooling. At the same time, "semi-winding" technique provides fibre tension that is a key feature of filament winding and makes wafer panel characteristics similar to the whole fuselage section ones.

To create panel skin that has characteristics similar to the skin of the real-scale fuselage section to be produced by filament winding, it was proposed to wind impregnated fibre on the conventional winding drum to produce unidirectional carbon fibre tape. After that, obtained unidirectional tape was cut out and laid up to generate ±45° structure of the panel skin workpiece.

To correlate with selected OoA approach to be used for fuselage section production, it was decided to realize test panel curing in the oven using conventional vacuum bag.

To cast flexible silicone mould special female tooling with 3D printed master-model (Figure 2) was used. After it, silicone mould was installed on designed and produced rigid metal base to create combined tooling (Figure 3) to be used for manufacturing process realization.

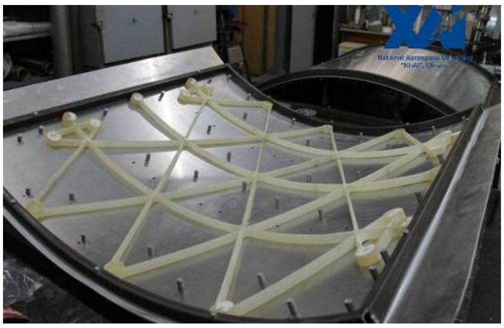


Figure 2. Female tooling with 3D printed master-model for shape-generating silicone mould casting

Figure 3. Combined tooling for wafer test panel manufacturing within installed semi-loop reels

2.3 Production of regular wafer test panel and wafer test panel with opening

To produce test panels the high strength/standard modulus aerospace grade carbon fibre HTS40 12K (800tex) supplied by the Toho Tenax© was used in combination with the Araldite LY 556 / Aradur 917 / Accelerator DY 070 480 hot curing epoxy matrix systems from HUNTSMAN intended for filament winding (pot life > 2400 minutes). Mentioned materials are used for both lattice structure and skin manufacturing. Specially designed semi-loop reels were preliminary manufactured using conventional metal working techniques from stainless steel 45X (GOST 4543-71) with further reels surfaces preparation and additional application of sub-layer for adhesive joint strength increasing.

Combined tooling (Figure 3) with replaceable silicone mould (different for regular panel and panel with opening) and installed semi-loop reels was used for test panel manufacturing. Process started with manual semi-winding of lattice structure following optimal winding routes developed separately for both types of panels. Winding routes ensure uninterrupted winding of ribs with minimum number of filaments used. In case of panel with opening, developed winding route also ensures all-round supported opening generation without following ribs cutting.

After this stage wounded lattice structure was covered with a skin workpiece (prepared as it is described in the previous section) and the additional metal stripes to be used for test panel fixation in the test jig were installed. Then the entire tooling was placed into the vacuum bag and 12-hours vacuum pressure exposure was realized to provide appropriate material compaction and to delete volatile products before the start of panel OoA curing according to the cycle recommend by the resin manufacturer. Standard techniques of non-destructive inspection were applied to the produced test panel to validate its quality.

Photos of representative panels that are ready for pre-testing procedures are presented at the Figure 4. In total, two regular wafer panels and two panels with opening were produced to realize experimental research described in the next section.

Figure 4. Regular wafer test panel and wafer test panel with opening

2.4 Analysis of developed manufacturing process and tooling peculiarities

Based on the results of preliminary research and taking into account experience gained during wafer test panels manufacturing, efficient solutions of key bottlenecks in wafer structures production were developed:

- *Two and three ribs intersection*: reliable method of ribs intersection area design was developed to ensure optimal material re-distribution, constant ribs height and smooth changing of fibre volume content is these areas.
- *Semi-loop reels design*: basic ratios of rib cross-section and semi-loop reels geometry were clarified to ensure feasibility of lattice structure generation and optimize reels manufacturing time and costs.
- *Reliable joining of lattice ribs and semi-loop reels*: different combinations of semi-loop reel materials, surface treatment methods and sub-layers compositions were assessed experimentally to select those ones that ensure high bonding strength, thus providing opportunity for semi-loop joints optimization in terms of weight and dimensions.
- *Appropriate fibre volume content*: influence of silicone compound parameters (CTE and rigidity) on lattice structure material compaction was studied to develop recommendations on selection of appropriate silicone compound that ensures generation of required internal pressure as a result of silicone mould thermal expansion during the curing stage.
- *Accurate structure geometry and dimensions*: common approach to silicone mould design (including silicone compound selection) that ensure both structure high-quality and manufacturability was developed and validated in practice.

Following the general approach described in the beginning of this section and using developed methods and techniques, cost-efficient manufacturing process could be built for any wafer structure that includes integrated dual-purpose semi-loop joints.

3. Testing

3.1 Fuselage loads analysis

Load analysis for full-composite wafer fuselage section (see Figure 1) was performed using appropriate data for the P180 Avanti from Piaggio Aero Industries that was used as a reference airplane during the design phase. Estimation of loads according to the CS23 rules resulted in forces distribution for different flight and ground load cases. According to the calculated data, maximal values of operational forces were realized for the load case CS23.481-Tail down landing with MTOW. Analysis of bending moments and shearing forces distribution in the fuselage section allows to specify four areas that have different load conditions: the upper part of fuselage section is primarily loaded by tension, the bottom area is mainly compressed, and side areas are generally loaded by shear.

Preliminary FEM simulation of fuselage section, which was designed to withstand above-mentioned load case, predicted the wafer-structure failure as a result of skin buckling in bottom (compressed) zone. Considering technical complexity of full-scale fuselage bending tests, compressive test was selected for experimental validation of developed fuselage design. Following this way, the compressive tests were planned for full-scale curved wafer test panels (Figure 4). Magnitudes of compressive load to be applied for wafer panels were calculated in concordance with operational loads in specified areas of fuselage section using both FEM simulation and analytical approach based on the theory of thin-walled structures. These values are equal to 72 kN for the regular panel which represents the bottom part of the fuselage section, and 21 kN for panel with opening in concordance with forces distribution in side areas of a fuselage.

3.2 Test scheme

Common approach which is used for testing of curved wafer panels or traditionally stiffened panels supposes designing and manufacturing of special test fixtures of the panel edges to realize simultaneous loading of skin and stiffeners (ribs or stringers) [4, 5]. According to the main WASIS project idea [1], integrated semi-loop reels are used to join composite lattice reinforcing structure with metal attachment frames (Figure 1) and to provide efficient loads transfer. That's why the easiest testing method of the wafer panels is compressive test or tensile loading directly through the reels (see 3 reels on the top and lower edges at the Figure 4).

However, results of FEM simulation of the fuselage section indicated that skin of the designed wafer structure bears approximately 30% of bending loads and about 65% of shear loads. Moreover, any wafer panel has no common straight centroidal axis. This fact leads to the difficulties in definition of compressive load application point that ensures pure compression of wafer panel without longitudinal bending. To avoid this problem, an innovative approach for curved wafer panels testing was developed and realized in practice. It is based on simultaneous testing of two wafer panels fixed in specially designed test jig that imitate fuselage attachment frame (see Figure 5).

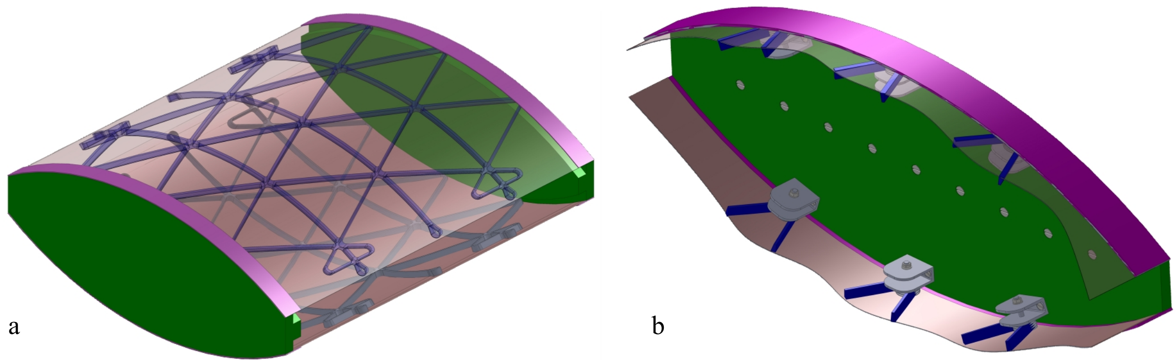


Figure 5. Basic approach for compressive test setup of curved wafer panels (a) and test jig in detail (b)

3.3. Experimental setup

Mechanical testing of two types of wafer panel presented above was conducted at the Aircraft Strength and Reliability Testing Laboratory* of the National Aerospace University "KhAI". Compression tests were performed using the universal testing machine GRM1 with load limit of 200 kN (see Figure 6) and measuring strain-gage system SIIT–3. Analysis of responses of the wafer panels were executed according to the data provided by 20 strain gauges mounted on internal and external surfaces of the panel skin within the panel testing zone, and 10 strain gauges mounted on the ribs.

Testing procedure consisted in preliminary loading and adjustment of tensometric system, then step-by-step loading up to the operational loads with sequential reading of the strain gauges values, unloading, reading of strain gauges values for residual strains assessment and final panels loading up to the structures failure. The load limit of testing machine considering the developed approach to the testing caused the restriction of applied compressive force per one panel up to 100 kN providing 139% of operational load for the regular wafer panel.

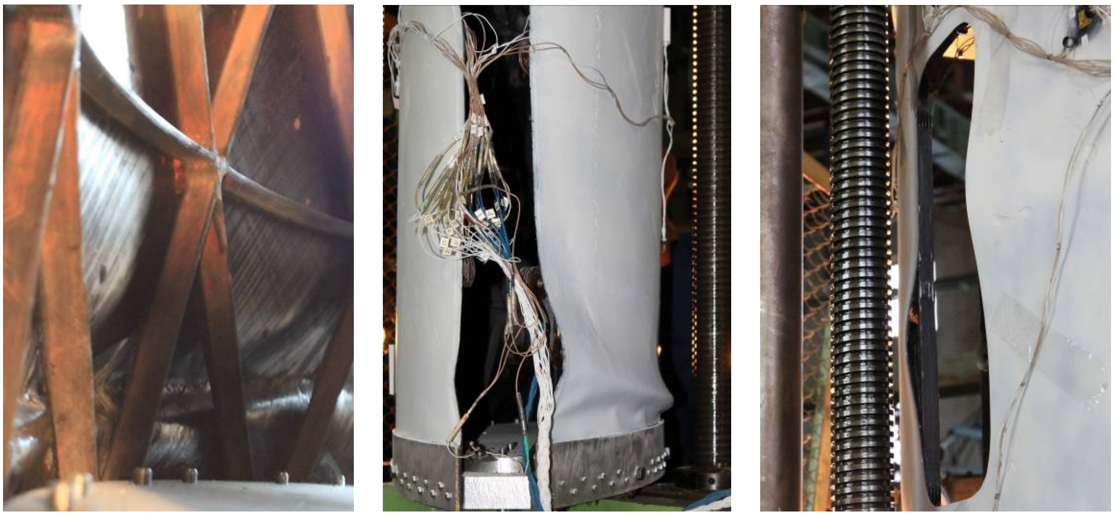
* Aircraft Strength and Reliability Testing Laboratory is certified by Aviation Register of Ukraine with delegation of the rights to perform certified works and examinations in the field of aircraft durability.

a b

Figure 6. Regular wafer panel (a) and wafer panel with opening (b) mounted on testing machine

3.4. Experimental results analysis

The first observed damage of the regular wafer panel occurred at 118% of operational load (85 kN per one panel) due to the skin-to-ribs local debonding. Propagation of damage of one of the tested panels was caused by the peel-off failure of adhesive semi-loop joints of ribs and reels. Further buckling of the skin provoked skin-to-ribs debonding (Figure 7, a) and complete destruction of one panel in the clamping zone (Figure 7, b). The only observable damage of other regular wafer panel was local debonding of central hoop rib near the longitudinal edges. The registered value of ultimate failure load during the testing reached 197 kN (98.5 kN per one panel) that corresponds to 137% of operational load of the regular wafer panels.



a b c

Figure 7. Ribs-to-skin debonding (a) and global buckling of skin of regular wafer panel (b) and debonding of longitudinal cut-out reinforcing ribs caused by buckling of edges in wafer panel with opening (c)

The value of ultimate failure compressive load of wafer panels with opening during the testing was not registered because of exceeding of machine limit (200 kN), so it will guarantee the required margin of safety for this type of panel under compression. After monotonous panels loading up to 60 kN (30 kN per one panel) and subsequent unloading there were no any visible residual strains. Local buckling of the cut-out edges (see Figure 7, c) occurred at 153 kN (76.5 kN per one panel). Buckling of the skin between spiral and hoop ribs of the panel was observed at 197 kN (98.5 kN per one panel).

Comparison of FEM simulation results and experimental data showed a good correlation (all deviations not exceed 20%). Thus, the validity of analytical approaches and FEM simulation procedures for design of composite wafer fuselage section with integrated semi-loop joints was confirmed. More detailed information on testing results and comparative analysis with the numerical results of FEM simulation will be presented in the future works.

4. Conclusions

General concept of manufacturing and testing of composite wafer structures with dual-purpose hybrid semi-loop joints was developed. Technical feasibility and efficiency of presented concept was shown via manufacturing and testing of real-scale curved wafer panels (regular one and the one with opening).

For this purpose the detailed manufacturing process was developed and realized manually through the use of specially designed and manufactured combined tooling. The description of manufacturing cycle is supplemented with the analysis of process peculiarities and references to possible solutions of key bottlenecks.

Based on produced panels geometry, special test jig was designed and manufactured to realize simultaneous testing of two wafer panels proposed as an alternative to the full-scale fuselage testing. Test loads were carefully estimated on the basis of advanced FEM simulation of integral wafer structure and realized during the testing with continuous control of wafer panels stress-strain state. Analysis of test results confirmed the validity of analytical methods and FEM techniques used for design of the full-scale fuselage section with the integrated attachment frames.

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