COMPOSITE RIB DEVELOPMENT

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ABSTRACT

The development of carbon fibre reinforced epoxy resin ribs for a demonstrator commercial aircraft wingbox is described. The complex geometry ribs were manufactured using the Resin Transfer Moulding (RTM) method. The ribs were designed according to typical load cases for commercial aircraft, and the designs were substantiated by a series of structural element tests. The RTM process was optimized using a purpose built trial tool, assisted by commercial resin flow visualization computer software. Data from the trials and measurements from elements were used for part tool design. The ribs were produced according to aircraft production quality standards, and were supplied for assembly into a wing test article.

1.INTRODUCTION

Israel Aircraft Industries (IAI) is one of the more than 30 companies participating in the European Commission 5th. Framework R&D Programme 'TANGO'. This programme is aimed at developing the new materials and processing infrastructure required for the next generation of commercial transport aircraft, with the targets of 20% reduction in both cost and structural weight. Four major components are being built and tested, a composite lateral wingbox, a composite wing carry through structure, a composite fuselage barrel and an advanced metallic fuselage barrel. IAI is assessing some bonding technologies on the metallic fuselage barrel, and has manufactured various ribs for the lateral wingbox. The ribs manufactured by IAI use the Resin Transfer Moulding (RTM) method, incorporating a high temperature capability matrix resin and a low-cost high-performance non-crimped carbon fibre fabric. The geometry of the ribs is complex, incorporating sine wave bead stiffened thin webs, integral caps for cover attachment and cutouts for fuel system component and cover stringer clearance. Since the ribs were to be assembled to other wingbox components, the upper and lower covers, front and rear spars and fuel system details, dimensional accuracy was important. The complex geometry of the ribs and the close tolerance assembly requirement directed the selection of RTM as the manufacturing method.

The development programme for the ribs comprised preliminary design and material selection, manufacturing process development and substantiation of the selected design concept. Data derived during the process development and substantiation stages was used for final rib and tool design. Rib manufacture was to aircraft production quality standards, with fully traceable documentation.

2.PRELIMINARY DESIGN & MATERIAL SELECTION

Since one of the drivers of the TANGO programme was cost reduction, the decision was made to design ribs with all features integral so as to minimize downstream assembly costs. An I-beam rib was selected, with integral stiffeners on the web to enhance buckling stability. Initially, the use of foam cored bead stiffeners was considered, but a test programme demonstrated the superior buckling performance of the sine wave geometry. Additionally, the sine wave geometry is more readily producible, due to fewer problems with fabric drape at the stiffener run-out. A further consideration was that since the wingbox is a fuel tank, the use of foam in fuel-wetted areas is contraindicated. For these reasons, the sine wave stiffened web was selected.

Prior experience at IAI had shown that the use of ribs with sine wave stiffened webs is not straightforward. If the stiffener continues the full height of the web to the web/cap junction, and the web plies transition into the cap, the fabrics in the plies are grossly distorted. This causes major difficulties in both manufacture and detail component stress analysis. Accordingly, an innovative design concept was selected, in which the stiffener bead stops short of the rib caps. The stiffener terminated in a run-out in the thick area of the web, required by bolt bearing strength considerations, adjacent to the cap. Web and cap cut-outs were designed to be trimmed by waterjet equipment following manufacture of a part with a complete web and caps. Producing the cut-outs as an integral part of the RTM process is feasible technically, but was considered uneconomic due to the complications involved with tool design, ply cutting and lay-up.

Low cost raw materials were selected, to meet the goal of cost reduction. All reinforcements used were non-crimped carbon fibre fabrics (NCF) produced by warp insertion knitting using a low tex polyester knitting yarn. The fabrics used were Devold Types 2A, 2B and 7, according to Airbus Specification RDR 1-0024, incorporating Tenax HTS 12k fibre. The Type 2 fabrics contain fibres in $\pm 45^0$ and 90^0 directions, and the Type 7 fabric is unidirectional in the 0^0 direction. The 2A and 2B variants are of opposite chirality. In addition to the low fabric cost, the relatively thick plies, compared to conventional woven fabrics, result in savings due to reductions in the number of plies required in a lay-up.

The choice of resin was not straightforward. Prior development of RTM technology at IAI had demonstrated the economic benefit of low temperature processing. Gelling matrix resins at low temperature is also a significant aid to reduction of thermally induced distortions in parts after cure. However, the operating temperature requirements for the TANGO wingbox dictated a minimum ‘wet’ resin T_g of about 140^0C, i.e. a ‘dry’ T_g of about 180^0C. There are few resins that meet both these requirements. A development polyfunctional epoxy cured with a cycloaliphatic amine hardener resin system was selected, that could be processed and gelled at about 60^0C, and after appropriate cure and post cure could achieve a T_g of about 200^0C. A series of laminates was manufactured to measure basic lamina and laminate properties. Mean fibre volume fraction was 58%; void content was typically in the 0.5-1% range. Microscopic examination of polished sections revealed a laminate structure incorporating localized resin rich triangular regions surrounding the polyester knitting yarns of the NCF fabrics, as shown in Fig.1.

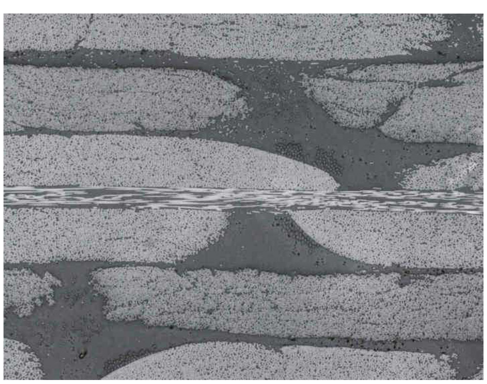
Fig.1.Typical NCF microstructure.

Any porosity in the microstructure tended to accumulate in these resin rich areas. Mechanical properties measured included, in addition to the basic lamina parameters, open and filled hole tension, open hole compression, bolt bearing, fatigue and compression after impact. Hot-‘wet’ properties at 80^0C were used for deriving data for rib design.

3.MANUFACTURING PROCESS DEVELOPMENT

The TANGO wingbox contains 15 composite ribs, of which 3 were manufactured by IAI [1]. These were the highly loaded rib 2 close to the wingbox root, rib 5 incorporating a highly loaded fitting for reacting flap track actuator loads, and the relatively lightly loaded rib 13 close to the wingbox tip. A trial RTM tool was designed and constructed, containing potential design features of all three ribs. These features included sine wave stiffening beads on a variable thickness web and integral I-beam caps. The tool incorporated multiple ports for resin injection and venting so that the optimum RTM resin flow strategy could be determined. Tool steel W1.2312 per DIN 17350 was used for construction of all the major components of the tool. The tool was designed to net part shape; no thermal corrections were included in the tool design. The laminate design within the part was similar to that proposed for the final ribs, incorporating fibres at angles of $\pm 45^0$ and 90^0 to the long axis of the ribs, to a nominal 58% fibre volume fraction.

Fabrics were coated with a commercial powdered epoxy binder by electrostatic spraying, and were preformed onto the tool components in an oven using vacuum bag pressure. Conformal cast silicone rubber mandrels were used as pressure intensifiers to assist preforming the NCF plies, particularly to the sine wave geometry, due to the very limited drape of these fabrics. The radii between the caps and the web were filled with rolled strips of the type 7 fabric, the quantity calculated to achieve the same fibre volume fraction in the radii as in the rest of the part.

Initial RTM trials produced parts with dry areas at one end of the web, adjacent to the caps, as a result of suspected resin racetracking along the caps. Attempts to improve this by closing off resin injection ports adjacent to this area produced larger dry areas. This behaviour was not understood, but further trials in which resin injection ports at the opposite end of the web from the dry areas were closed off produced completely wetted good quality parts. This behaviour was analysed using the RTM-WORX resin flow simulation software from Polyworx, see Fig.2, which predicted the observed phenomenon. It seems that the problem arose as a consequence of the variable web thickness; resin flow was faster in the uniformly thicker areas of the web distant from the dry areas and this allowed rapid resin flow to the caps and consequent racetracking.

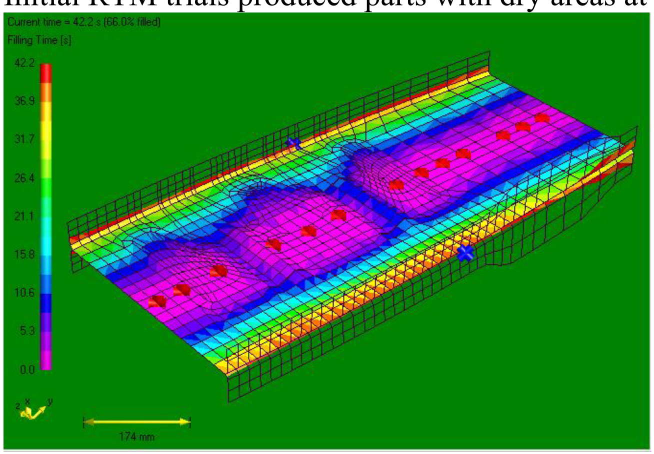

Fig.2. Resin Flow Simulation for Rib Element

Good visual quality parts were examined by X-ray and ultrasonic non-destructive test (NDT) techniques and by CMM dimensional measurement. Other than some waviness of the web/cap junction radius fillers and localized porosity in areas adjacent to the fillers, NDT revealed no problems. CMM measurements showed small but consistent dimensional and springback discrepancies compared to the design geometry. This data was used to correct for thermally induced part distortion during design of the tools for the actual wingbox ribs.

The trial components were cut into several element configurations for substantiation testing of various structural details of the design. Offcut samples were examined microscopically and were tested for laminate physical properties. Low porosity levels were observed, typically in the 0.5-1.0% range. As for the flat panels, any porosity observed in the laminates tended to be concentrated in the triangular resin rich areas surrounding the polyester knitting yarns. Glass transition temperature (E' midpoint) was measured on offcut samples using flexural TMA, and was typically in the range 180-210^{0}C.

4.DESIGN CONCEPT SUBSTANTIATION

The components of an aircraft wing are loaded in several modes, often simultaneously. Straight and level flight results in wing flexure and torsion during lift generation. Manoeuvering loads alter the magnitude and ratio of these forces. The fuel tank area is usually pressurized, and changes in aircraft attitude can add fuel sloshing loads to the pressurization affects. The ribs were designed to operate according to specific load cases supplied for the TANGO wingbox. The various element tests carried out demonstrated that the ribs could operate safely at all the design load cases. Tests carried out were web shear with and without penetrations, web compression, web flexure and pull-off tension and cantilever bending of the web/cap junction. In all cases, the design details withstood the expected loading, with adequate safety factors. Combined load cases were not tested. These were analysed and will be tested during loading of the final assembled wingbox.

4.1.Web Shear

Torsional deflection of the wingbox loads the rib webs in shear. This was simulated by a picture frame test of a panel with a design similar to that of the rib webs. The panel was manufactured incorporating two sine wave beads in a central thin area, with a peripheral thickness increase for attachment into the picture frame shear loading fixture. The panel thicknesses were those designed for corresponding areas on ribs 2 and 5. After monitoring the elastic buckling behaviour of the panel using back to back strain gauges, the panel was removed from the test fixture. Holes and slots were cut out of the panel of sizes and locations representative of fuel system component penetrations and clearances for the stringers on the wing covers to which the ribs would be attached. The panel was reinserted into the test fixture, and retested, as shown in Fig.3. It was found that the 4 mm. thick sine wave stiffened web was equivalent in buckling performance to an 8 mm. thickness web with no stiffeners. Penetrations did not affect stability; the stress concentrations around the various penetrations were in the range 3.2-4.6.

Fig.3.Web Shear Test with Penetration

4.2.Web Compression

The web of the rib is directly loaded in compression during flexure of the wingbox. This load case was tested using an element extracted from one of the RTM process development articles. The element was liquid shimmed and bolted to metal end fittings representing sections of wingbox covers. Liquid shimming was necessary since the caps were curved, and additionally one cap was not perpendicular to the web, as would be the case for a wing rib. A stringer clearance cutout was machined at one end of the element. Metal shear ties were bolted to the composite element and the end fittings on either side of the cutout. This design feature incorporated into the ribs was adopted since joggling the cap for direct attachment of the rib cap to the feet of the cover stringers was contraindicated due to assembly tolerance considerations.

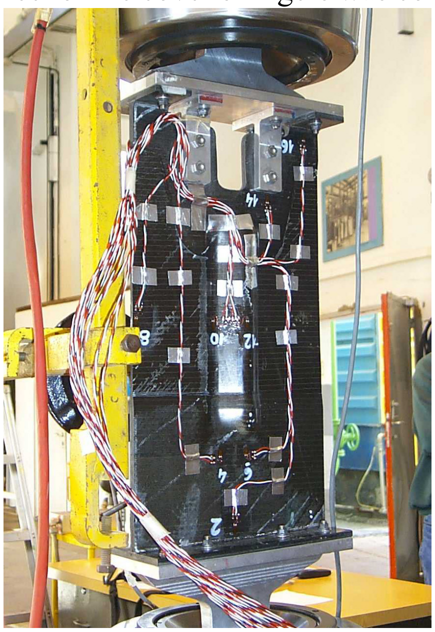

Fig.4.Compression Buckling Test.

The element was instrumented with an array of back-to-back strain gauges in critical locations, as shown in Fig.4. The element was loaded well into the elastic buckling region. Buckling instability initiated at about 5000 microstrain. The test was discontinued at an applied load about three times the design load, with no damage apparent.

4.3.Web Flexure

The web of the rib is subject to differential fuel pressure loading that can arise during fuelling, tank-to-tank fuel transfer and sloshing as a result of aircraft manouevre. This was tested using an element with the same geometric configuration as that for web compression, using a different loading method. In this case the liquid shimmed and bolted end plates provided lateral support, and load was applied using bonded loading pads and a load spreader plate on one side of the web. This element was loaded to five times the design load, with no indications of failure.

4.4 Cap to Web Tension

The junctions of the caps to the web experience tensile loading as a result of fuel pressurization of the wingbox. This was tested by cutting elements from these junction areas. Elements were cut from both top and bottom caps, since in one case the cap was designed to be not perpendicular to the web. The elements were assembled to a metal T-fitting by liquid shimming, jigging the assembly to ensure that the element web and the fitting web were in line. The elements were drilled, and bolts inserted of diameters and spacing representative of the real design cases. During tensile testing, a noise was heard together with the observation of a small load drop. The elements continued to carry loads to much higher values than the initial load drop prior up to final failure. Failure was by the formation and coalescence of cracks at the boundary of and within the approximately triangular filler fillet at the web to cap junctions. The initial load drop occurred in the range 1.1 to 1.3 times the worst case design load. Elements with the web perpendicular to the cap behaved similarly to those with web and cap not perpendicular.

4.5.Cap to Web Cantilever Bend

The junctions of the cap to the web experience sideways bending load as a result of fuel sloshing during manouevering and as a result of differential fuel pressure from one side of a rib web to the other. T-elements were extracted from the trial parts, and the cap section was clamped into a fixture. The web section was loaded using a roller in a direction parallel to the cap. Initial failure occurred at about twice the design load, and the part continued to withstand load without ultimate failure. As for the tension tests, failure was by the formation and coalescence of cracks at the boundary of and within the approximately triangular filler fillet at the web to cap junction.

5.RIB MANUFACTURE

RTM tooling for the wingbox ribs was designed using similar logic to that for the trial part. Various improvements were incorporated as a result of the learning experience with the trial tool. Additionally, thermal distortion and springback corrections were designed into the tools, based on the CMM data from the trial parts. The tools were constructed using the same steel as for the trial part.

Fig.5. RTM Tooling and Conformal Mandrels

Part manufacture used the same methods as the trial parts, and was controlled by purpose prepared documentation defining every process step. Preforms were prepared directly onto the tool RTM segments using conformal cast silicone rubber mandrels and vacuum bag pressure, see Fig.5. Following tool assembly, the various resin flow manifolds were attached and the system was checked for vacuum integrity. Tools were heated under vacuum in an oven to the required injection temperature, and were then injected with resin using a dual cylinder meter, mix and inject RTM machine. Following tool filling, the vacuum system was isolated and the resin pressure increased. Following isolating and disconnecting the RTM machine, the parts were gelled at the same temperature as that for injection. Subsequently, the parts were cured and post cured in the tools.

Fig.6. Demoulded Rib 2 Before Trimming

Following demoulding, see Fig.6, all ribs were X-ray and ultrasonic NDT inspected and CMM dimensionally inspected. Overall part quality was good; some local areas of waviness and aggregated porosity were observed in the radius filler areas of the web to cap junctions in ribs 2 and 5. These areas tended to be concentrated towards the centre of these longer ribs. CMM inspection showed that all part dimensions met the overall tolerance requirement for the ribs of $\pm$0.2 mm with $\pm$0.1 mm tolerance in certain critical areas.

The ribs were trimmed to final profile using 5 axis high-pressure abrasive waterjet cutting equipment. Following trim, all cut edges were inspected by ultrasonic NDT to confirm the absence of any damage caused during trim. Pilot holes were then drilled into the caps and web, for defining drilling and bolt locations for final assembly of the ribs to the wingbox covers and front and rear spars. The ribs were then repeat CMM dimensionally inspected, to check the location of trim cutouts and the pilot holes. During this inspection, it was evident that there was no relaxation of cap to web springback angles as a result of trimming away substantial areas of the web to cap junction area.

At this stage, all ribs were painted using a chromate free urethane compatible composite primer per BMS 10-103. All parts for the wingbox assembly were supplied using this or a similar pale coloured primer. The purpose of the primer was to make the assembly process easier, since visual observation and monitoring of assembly operations inside a closed box in which all the details are black is difficult. Ribs 2 and 5 were supplied as assemblies including metal fittings. The fittings were located and match drilled to the ribs using purpose constructed assembly tools. The fittings were liquid shimmed to their correct locations as defined by the assembly tools, and the attachment bolts were torqued into place using a polysulphide rubber sealant interfay between the bolt shanks, the rib web and the fittings, as shown in Fig.7.

Fig.7. Trimmed and Painted Rib 5 with Assembled Fitting

Following final inspection, the parts were shipped for wingbox assembly together with the shear ties and fasteners and complete production tracking and inspection documentation. At the time of writing the various components of the wingbox are being assembled in preparation for structural testing, as shown in Fig.8.

Fig8. TANGO Lateral Wingbox during Assembly

6. CONCLUSIONS

Many valuable lessons were learned during this development exercise, as follows.

- The substantiation of the design of the partial height sine wave stiffening bead was an important achievement. The weight saving potential of the sine wave web is well known, but practical difficulties have prevented its widespread adoption for composite material parts. The partial height design concept provides a method for exploiting sine wave geometry while minimising the practical difficulties.
- The use of non-crimped fabrics has both positive and negative features. The fabrics are relatively inexpensive, and can reduce lay-up effort via reduced ply count. However, their drape is very limited compared to conventional woven fabrics. Also, the unidirectional NCF is unstable, tending to change fabric width (and hence ply thickness) during handling.
- The development resin used met the low injection and gel temperature and high glass transition temperature requirements, but was brittle. This brittleness was exacerbated by the NCF architecture, with the array of relatively large resin rich areas at the knitting thread locations. These together resulted in only modest toughness related properties for the final laminate material, such as compression after impact and open hole compression. The level of these properties is frequently a problem for typical resins suitable for RTM processing, but the problem seems to be exacerbated by the NCF morphology.
- The use of resin flow simulation software was a valuable process development aid, enabling qualitative assessment of the curious phenomena observed during the initial stages of development of RTM processing. The use of this software is being extended to incorporate part and tool design and use for quantitative control of RTM production processing.
- The overall programme provided a good vehicle for building a data base for RTM tooling design. This included two main aspects; methods for calculating thermal distortion corrections, and optimization of tool detail design to make routine production more efficient.
- R&D personnel carried out the development exercise. However, the emphasis of the TANGO programme was to manufacture parts to aircraft production quality standards. The quality control methods and level of documentation this necessitated imposed a good working discipline on the R&D personnel, while still maintaining the flexibility necessary.
- Exposure to the differing manufacturing methods being developed and the different working practices of the other TANGO partners was a valuable experience. The interactive nature of much of the work produced cross-fertilisation of ideas derived from the diverse prior experience of the companies involved.

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