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Development of Vacuum Enhanced Resin Infusion Technology (VERITy) Process for Manufacturing of Primary Aircraft Structures

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Abstract | Liquid Composite Moulding (LCM) is the process in which resin is infused into dry fabric and formed in the mould cavity under vacuum/closed moulds. This process has been the workhorse of marine industries for many years primarily due to relatively low cost of production. The advent of new and improved resin systems and suitable reinforcements makes infusion process and its variants more feasible for demanding aerospace applications. Many variations of this process like the SCRIMP (Seemann Composite Resin Infusion Moulding Process), VARTM (Vacuum Assisted Resin Transfer Moulding) have made significant progress. More recently, VARTM process is being explored by many in the industry for manufacture of primary structures for aircrafts. CSIR-NAL too has developed a proprietary infusion process called **V**acuum **E**nhanced **R**esin **I**nfusion **T**echnolog**y** (VERITy) for manufacturing of primary composite components. The major objectives this development were two-fold; namely to enhance the effectiveness of infusion process by nearly equaling mechanical properties similar to prepreg parts with fibre volume fraction approaching 60% and making the process cost effective for manufacturing large sized and complex composite components. Industry standard building block approach as per CMH-17 was used for the development of the VERITy process. The activities spanned from manufacturing large number of laminates for evaluating mechanical properties to the development of a large test box for structural testing to demonstrate the processing technology developed. Proper design of experiments and necessary qualification tests were done at each level to understand the nuances of the process. The study included selection of a suitable epoxy resin system, reinforcement (carbon unidirectional fabric) and consumables for infusion like resin distribution medium. It also involved understanding cure kinetics, characterization of resin system and its flow characteristics under vacuum. The resin infusion window (RIW) and pressure application window (PAW) were established. The cure cycle of the resin system was established in order to achieve required fibre volume fraction. Extensive evaluation of mechanical properties was done at three environmental conditions namely room temperature-dry (RTD), elevated temperature-wet (ETW) and cold temperature dry (CTD). Joints, panels and a test box were designed and manufactured, demonstrating the scalability of process to large and complex structures.

Keywords: *VERITy, Resin Infusion Window, Pressure Application Window, co-curing, low cost manufacturing, NDE.*

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1 Introduction

Primary composite parts in an airframe are traditionally made using carbon/epoxy prepregs with autoclave moulding. This process results in parts which are well consolidated with good mechanical properties due to the high volume fraction of fibers & low void content. However there are certain limitations with this process which have cost implications viz.

Prepreg: The reinforcement in the form of mat or fibres impregnated with resin and stored for use.

a. Prepregs are shelf life items that require maintenance of temperature during transportation and subsequent storage typically at −18°C.
b. Lay-up of prepregs requires clean room facilities where the dust particle count, temperature and humidity have to be maintained.
c. Time for lay-up is limited by shelf life, which may again limit the amount of co-curing on a larger component.

Co-curing: Simultaneous curing of 2 or more components

Researchers have been contemplating alternate processing techniques like liquid composite moulding (LCM) which are economical. There are many variants of LCM such as Resin Transfer Moulding (RTM), Advanced Vacuum Assisted Resin Transfer Moulding (A-VaARTM),[1] SCRIMP,[2] FASTRAC[3] etc. The infusion processes are typically a three-step process including lay-up of a fiber preform, impregnation of the preform with resin, and cure of the impregnated panel. In order to reduce the impregnation time, a resin distribution medium with a higher permeability than the preform[4] is used in these processes. These processes are assisted by vacuum in order to wet out the fibre preform. It has been shown that a vacuum assistance provides a significant improvement in mechanical properties. This is due to the higher fibre volume fraction and lower void content that can be achieved. The vacuum helps removal of air from within the fiber bundles, which results in lower void content. These processes are now being explored for manufacturing airframe structures. The Japan aerospace exploration agency (JAXA)[5] has developed wing structure using the A-VaRTM process.

VARTM processes are capable of manufacturing composite structures but have some limitations which include; dimensional requirements at infusion and vacuum end, uniform resin distribution within the part, removal of all the entrapped air, proper wetting of the fibre, clogging of resin and vacuum feed lines and the like. CSIR-NAL had gauged the pulse of industry ahead of time and initiated the development of a proprietary infusion process called VERITy (**V**acuum **E**nhanced **R**esin **I**nfusion **T**echnolog**y**). The process was aimed at increasing the fibre volume fraction and overcoming limitations seen by other infusion processes. The process also aimed to manufacture parts similar to parts produced by autoclave/prepreg technique through innovative means like integral tooling concepts, appropriate bleeder technology, smart flow sensors and hybridization with the autoclave moulding technology. It is important to achieve the optimum mechanical properties and stringent dimensional tolerances for these applications. The final goal was to develop the process that is scalable from a laminate level to a complex cocured primary structure like the wing of a transport aircraft.

The principle of VERITy is that the reinforcement is held in a tool cavity and infused with resin and a differential pressure is maintained using vacuum to impregnate fibers. Following are the advantages of VERITy process over the conventional autoclave process.

1. Relatively low cost for low volume production
2. Low cost of tooling

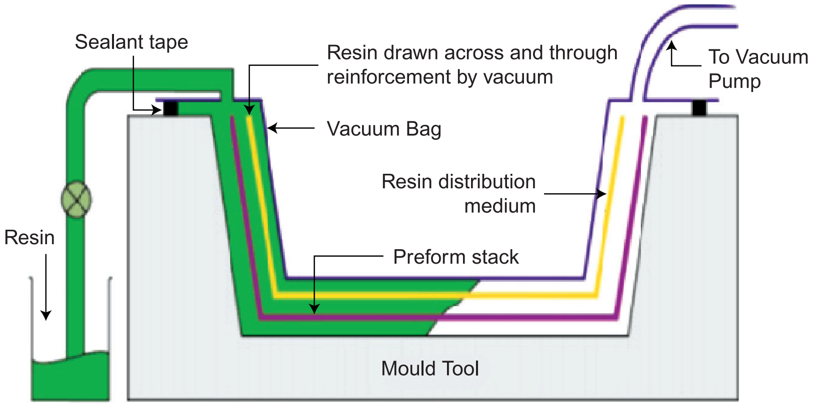


Figure 1: Schematic of VERITy process.

3. Possibility of manufacturing of very large and complex parts
4. High fiber volume fraction (58–60%) with low void content (less than 1%)
5. Properties equivalent to autoclave moulding possible

Figure 1 shows the schematic of VERITy process. In the VERITy process, the preform is loaded in the mould and resin is infused under vacuum. The impregnated preform is then cured in an autoclave. During cure, prior to gelation, an external pressure is applied in order to achieve required fibre volume fraction and better compaction, especially at cocured joints and thicker regions.

This paper brings out various challenges in processing that were encountered during scaling up of VERITy process to realise extensively cocured components of the wing of a transport aircraft. However, the detailed tooling & manufacturing process for sub-components and component levels is beyond the scope of this paper.

2 Building Block Approach

Any development program of a primary composite structure goes through a building block approach so as to mitigate risks and surprises at a later date. In this scenario, challenges were twofold; namely to substantiate the application of VERITy process to a large cocured structure and the structural performance simultaneously. The philosophy is to begin with small specimens and progress through structural elements and details, sub-components and finally to realize the complete full scale product. The knowledge is assimilated at each level and lessons learnt at previous, less complex levels are addressed progressively. A program was launched to understand the multitude of process parameters, flow patterns and tooling technology. The chronology of VERITy development with respect to technology readiness level vis-à-vis building block approach is as follows and pictorially depicted in Figure 2. The principal steps followed for development of VERITy process are indicated below.

1. Coupons level: Freezing of process parameters, Laminate characterization, Design allowable development
2. Detail & Element level: Tapered laminates, T-joints, Skin-Stringer panels, Spar splice, Skin splice joints
3. Sub component level: Full scale wing test box with major splice joints
4. Component level: Co-cured Top Skin, Co-cured Bottom Skin.

The following sections describe the research carried out at various levels to scale-up the process with a special emphasis on optimization of process parameters.

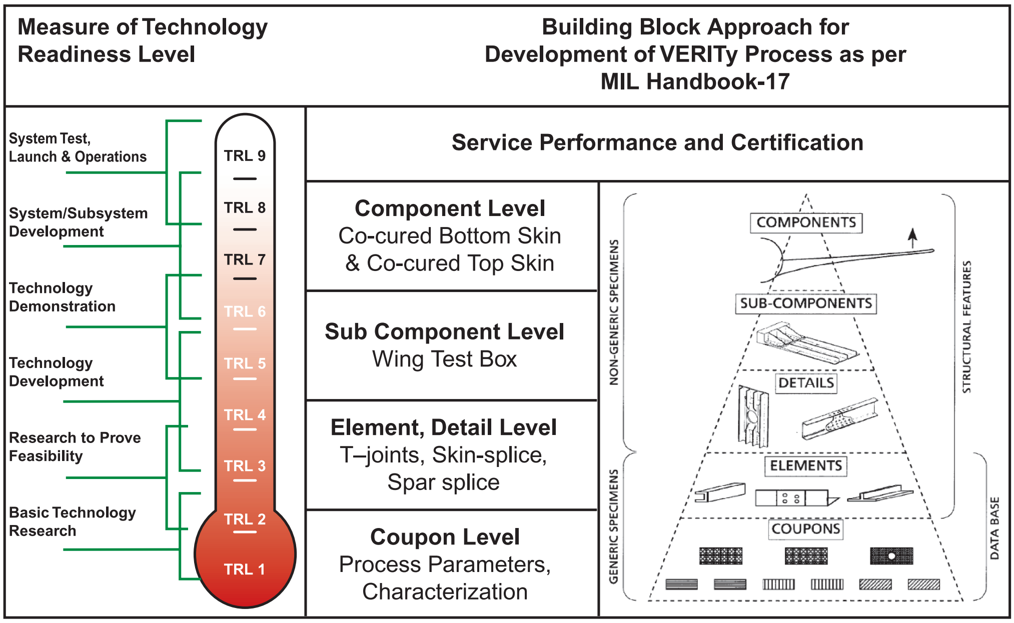


Figure 2: Chronology of VERITy process development.

Resin Infusion Window (RIW) : The time span in which the resin viscosity is maintained at particular temperature.

3 Material Selection

Selection of proper materials is of paramount importance as this determines the success of process and realization of desired properties on the part produced. Materials required can be classified into two categories namely (i) raw materials for manufacturing the part and (ii) consumables required for carrying out the infusion.

Raw materials: Widely used materials for aerospace structural parts are carbon fibre reinforcement with epoxy resin matrix. The fibre meeting both process and design requirements was selected; Toray T-300, G0827 BB1040 HP03 1F carbon unidirectional (UD) fabric manufactured by Hexcel Composites. This fabric has 97% fibres (carbon) in the warp direction and 3% (glass) fibres in the weft direction. Principal parameters for selection of a suitable resin system are viscosity, gel time, cure schedule and glass transition temperature (T_g). Two resin systems from different suppliers were chosen for evaluation. The first one was RTM 120 Resin system (RTM 120 resin and HY 2954 Hardener) from Hexcel Composites and other resin system was EPOLAM 2063 from AXSON Ltd. Preliminary tests were conducted on both the resin systems but EPOLAM 2063 resin system was selected based on viscosity profile and gel time. Rohacell RIST 51 (Resin Infusion for Structural Applications) foam was used for manufacturing of hat shaped stringers which can be thermoformed and machined to complex shapes.

Process consumables: The resin distribution medium (RDM) is one of the important consumables in this process. RDM should have a suitable permeability so as to permit resin flow rates that are suitable for VERITy process. Extensive experimentation was carried out to freeze a suitable RDM and a low flow knitted polyethylene mesh from Aerovac was selected.

4 Optimization of Process Parameters

4.1 *Resin characterization & establishing Resin Infusion Window (RIW)*

Prior knowledge of key properties such as resin viscosity and its variation with temperature, pot life and its variation with temperature are required to work out the infusion strategy to be employed. These properties will help in understanding the flow patterns. Both viscosity-temperature data and isothermal viscosity graphs were generated for the resin EPOLAM 2063 resin system.

In order to simulate the effect of reinforcement, a Brabender viscometer was used where the sample weighs 1 to 2 grams. For the RTM 120 system viscosity starts increasing after 30 minutes. From these measurements it was determined that the gel time at 45°C was 2.5 hours. This is very critical information as it is clear that infusion should be completed within 2.5 hours and full pressure should be applied before the resin gels. It was opined that this time may not be enough for infusion of large parts. This led to studies on Epolam 2063 resin system. Figure 3a shows the viscosity vs. temperature and fig 3b shows the viscosity profile at an isothermal temperature of 45°C for the EPOLAM 2063 resin system. In this resin system, the gelation starts at 45°C after about 6 hours. This information defines that the resin infusion window (RIW) is about 6 hours. Since the EPOLAM 2063 resin system showed larger resin infusion window and taking all the parameters into consideration, this resin system was used for further development.

4.2 *Establishing of infusion parameters*

The first objective was to make laminates that had similar quality from NDE aspects as that of the prepreg laminates manufactured using in autoclave. The fiber volume fraction in autoclave cured laminates is around 58–60% by volume and the void content less than 1%. In order to achieve these

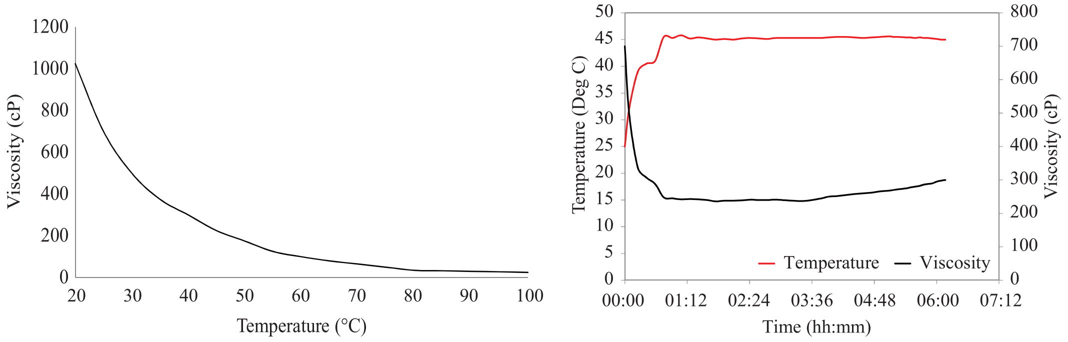


Figure 3: Viscosity characteristics of EPOLAM 2063 resins system. a) Viscosity vs. temperature, b) Viscosity v/s time at isothermal temperature of 45°C.

requirements many parameters had to be addressed. Some of the parameters studied were as follows.

a. Effect of mould (along with preform stack) heating and degassing prior to infusion
b. Effect of infusing excess resin
c. Effect of preforming and binder on the infusion process

A 2 mm thick laminate was chosen for the above study. In all the above cases the resin mixture was heated to 45°C, wherein the viscosity is around 200–250 cP. The resin mixture was infused at 45°C and cured at 80°C for 7 hours. The laminate was post cured at 180°C in free standing condition for 4 hours. The quality of laminate was determined by ultrasonic NDE. Coupons were cut to determine the basic mechanical properties so that process parameters could be frozen.

4.3 *Effect of mould heating and resin mixture degassing*

In the initial experiments, the resin mixture was heated to 45°C and infusion was carried out into the mould along with preform stack which was at room temperature. The ultrasonic C-scan attenuation levels were fairly high in the range of 7–12 dB. This was attributed the cooling of resin on contact with the preform which is at room temperature which led to increase in viscosity. At 30°C the viscosity is ≈600 cP and at 45 deg. C it is ≈200 cP. It was opined that the air could not be flushed out properly due to the high viscosity of the resin. In order to keep the required resin viscosity during infusion, the mould was heated to 50°C (a little more than resin temperature of 45°C) for further experiments. The NDE results showed significant improvement in quality but having attenuation levels in the range of 6–9 dB with some areas showing around 10–12 dB. The void content measured was 2–3% which was attributed to air bubbles that were present in the resin mixture during the mixing and could not be flushed out after infusion from the preform. In order to reduce the void content, the resin mixture was degassed for 15 minutes at 45°C prior to infusion. The NDE results showed the attenuation levels between 4–6 dB which is comparable to laminates made with a prepreg/autoclave process. The fibre volume was in the range of 57–59% which was equally good and the void content was less than 1%.

4.4 *Effect of infusion of excess resin mixture*

During the initial studies, excess resin (50%) was infused with the idea that this would ensure complete wetting of preform. However, it was repeatedly seen that the attenuation levels were lower at the vacuum side compared to the infusion side. It was also seen that the resin content on the infusion side was higher by about 5–8% as compared to the vacuum side. After many trials it was established that infusing the right amount of resin or an excess of a small percentage (amount ≤10%) resulted in better quality laminates. NDE studies and resin content studies on laminates showed that the attenuation levels and resin content were more uniform throughout the laminate. In the former case, the thickness was also more on the infusion side. This too became more uniform after infusing the calculated amount of resin.

4.5 *Effect of preforming and binder*

Unlike prepregs which readily adhere to the previous layer/tool surface on application of light pressure by a roller, the dry fabric does not adhere which is an impediment while laying up a complex is shaped part. In order to overcome this, the fabric having a binder of about 2–3% on its surface was selected. The binder is sprayed on the fabric surface during manufacturing of fabric. The binder helps layers to be preformed under heat and vacuum. This ensures better dimensional stability to the preform. Infusion was carried out on preformed fabric to study the effect of binder. It was observed that the progress of flow front was slower for the preformed fabric when compared to layer stack without preforming from a macroscopic wetting point of view. The slow movement of resin was due to a well-packed network of reinforcement. Ultrasonic scan of preformed laminate was same as that of one without preforming.

4.6 *Pressure Application Window (PAW)*

Pressure Application Window (PAW): Application of predefined external pressure during cure process at an appropriate time.

Generally, VARTM and its variants depend on the vacuum pressure for infusion as well as for consolidation. This could lead to areas of improper consolidation in a complex structure or lower fiber volume fraction. In order to overcome these drawbacks, a small amount of pressure was applied during cure. Dielectric measurements, using AUDREY dielectrometer instrument by Tetrahedron associates, were carried out to characterize the resin system during cure and determine the PAW. A Typical set-up for Dielectric measurement is shown in Figure 4.

This instrument concurrently monitors the dissipation factor (DF) of a sample as a function of time, temperature and frequency. The DF is sensitive to dipolar motion within the matrix of the composite, which is sensitive to the degree of advancement or cure of the resin. The dissipation factor has been recorded against time and temperature at constant frequency of 1 KHz. From these tests it was determined that the pressure to be applied after 30 minutes of dwell at 80°C.

In order to finalize the magnitude of pressure to be applied, controlled experiments were done on the laminate at different pressures. The fibre volume fraction test was conducted on the test specimens cut from these laminates. Based on the test results it was concluded that 1 bar external pressure would be the ideal pressure, which should be applied when the resin viscosity reaches about 900–1000 cP, which was also seen in the dielectric measurements.

Based on the above parametric studies following process parameters were frozen:

1. Mould along with preform to be heated at 50°C
2. Resin and hardener to be degassed at 45°C prior to infusion
3. Excess resin mix quantity to be ≤10%
4. Infusion to be carried out at 45°C
5. 1 bar external pressure to be applied when the resin viscosity reaches about 900–1000 cP (in case of EPOLAM 2063 resin system after 30 minutes of dwell at 80°C).

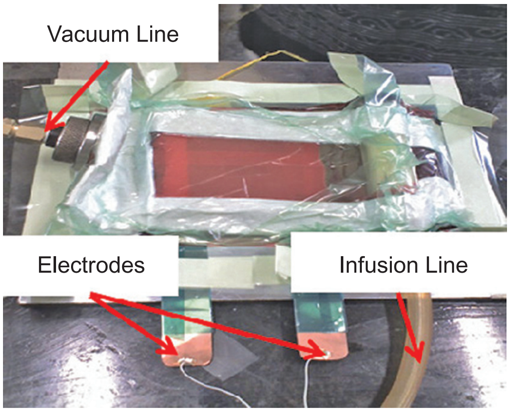


Figure 4: Dielectric measurement set-up.

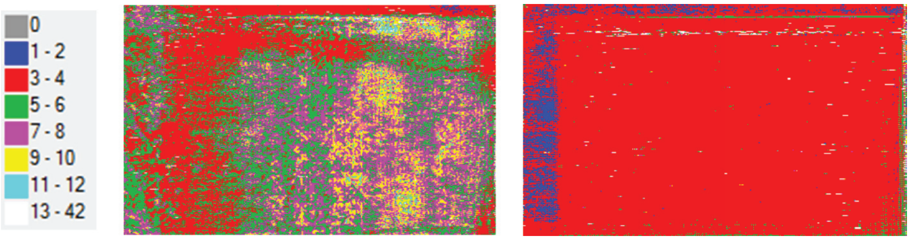
5 Coupon Level Processing

5.1 Fabrication of laminates of different thicknesses

Laminates with thicknesses ranging from 2 mm to 18 mm representing typical layups in a primary aircraft structure were manufactured. Figure 5 show ultrasonic plots of a 4.08 mm (24 layers) laminate before and after optimization. Figures 6 and 7 show the ultrasonic plots for 2 mm and 6 mm laminates fabricated by VERITy and prepreg processes. Figure 8 shows the 18.36 mm (108 layers) laminates fabricated by VERITy process. From the images it can be seen that the laminates made with the optimized process parameters are of excellent quality and comparable to autoclave cured laminates. The fibre content and void content were measured in various regions of the laminate and found very consistent. The fibre volume fraction was 57–59% and void content varies between 0.4 to 0.6%.

5.2 Evaluation of mechanical properties

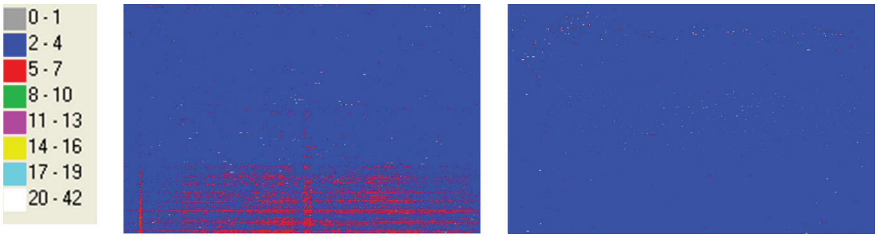
The first step in applying the building-block approach to the development of a composite structure is the quantification of mechanical



Before optimization

After optimization

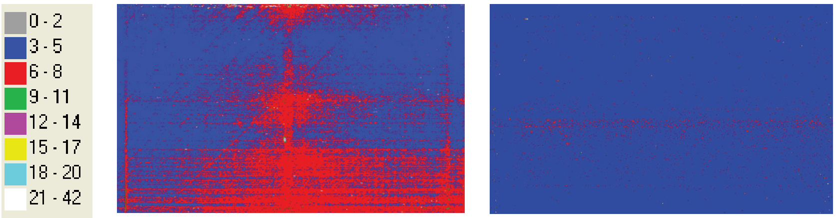
Figure 5: C-scan image of 24 layers (4.08 mm thick) laminate.



VERITy Lamiante

Prepreg Laminate

Figure 6: C-scan image for 2 mm laminate.



VERITy Lamiante

Prepreg Laminate

Figure 7: C-scan image for 6 mm laminate.

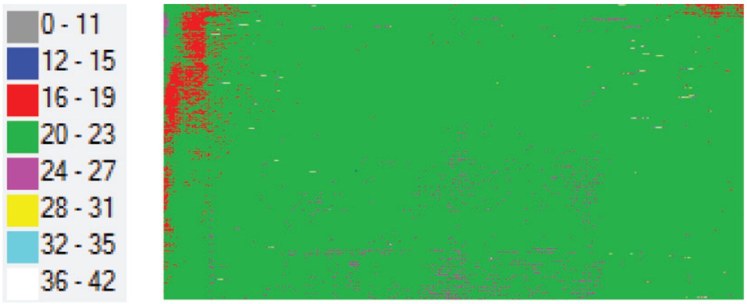


Figure 8: C-scan image of 108 layers (18.36 mm thick) laminate.

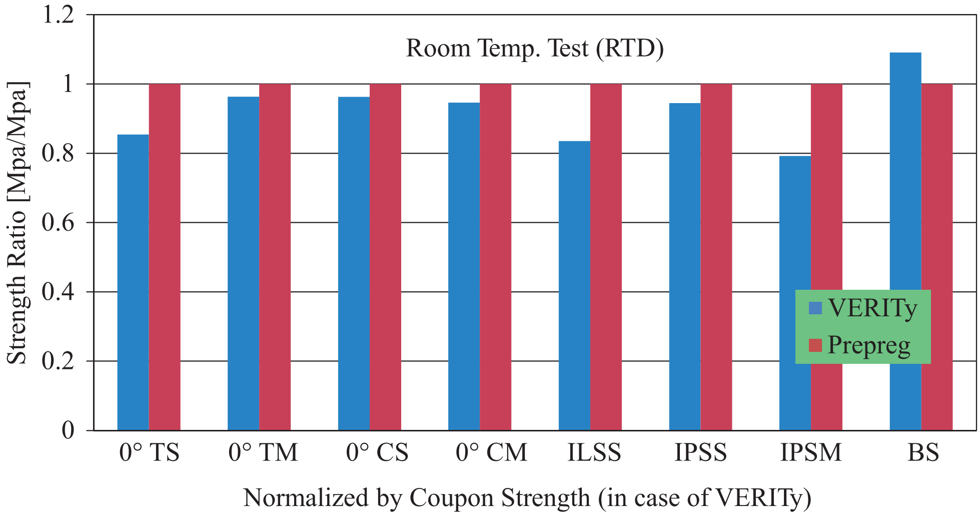


Figure 9: Comparison of mechanical test results at room temperature.

properties of the material being considered for the design. The coupon level tests were carried out at three environmental conditions namely room temperature dry (RTD), elevated temperature wet (ETW) and cold temperature dry (CTD). Selection of tests and test conditions were guided by composite material handbook CMH-17. An extensive coupon level test program was launched to establish basic lamina properties as per ASTM and other standards wherever applicable. The test parameters were reported based on the statistical methods recommended by CMH-17. Unidirectional lamina strength and moduli in tension, compression and shear were evaluated. Both un-notched and notched strengths at laminate level in tension, compression and shear were determined.

The comparison of mechanical properties for RTD condition with prepreg is shown in a Figure 9.

Specimens were conditioned in a specially designed environmental chamber at 71°C and

Room temperature dry (RTD), elevated temperature wet (ETW) and cold temperature dry (CTD): The matrix dominated properties of composites are sensitive to environmental condition. Different environmental test condition namely RTD (room temperature testing), ETW (high temperature testing after moisture saturation) & CTD (low temperature testing) at which the mechanical test carried out as per MIL handbook CMH-17.

85% relative humidity (RH). Control specimens were weighed on a weekly basis till the successive weights did not show appreciable change. A typical graph is shown in Figure 10. Elevated temperature wet properties were evaluated after ensuring complete saturation and testing was carried out at 71°C and 85% RH in a UTM using a specially designed test chamber. The water steam

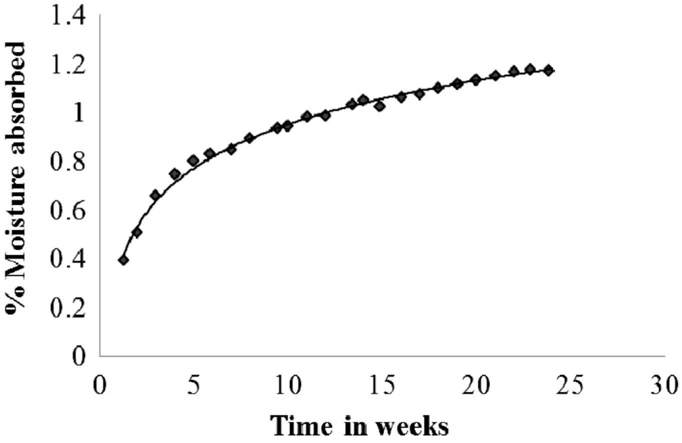


Figure 10: Typical moisture absorption graph.

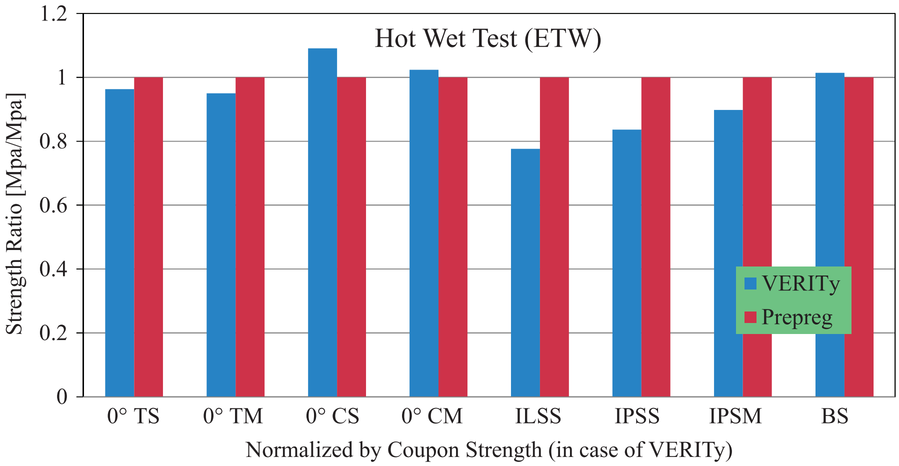


Figure 11: Comparison of mechanical test results at 71°C & 85%RH.

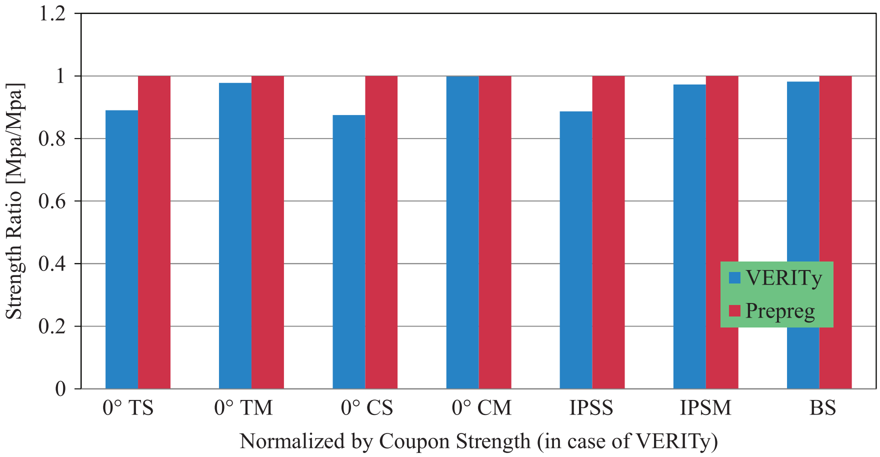


Figure 12: Comparison of design allowables.

was passed in the test chamber to achieve the desired RH and temperature. The comparison of mechanical properties generated for elevated temperature wet (ETW) condition is shown in a Figure 11.

The comparison of design allowables for VERITy and prepreg is shown in Figure 12. It is seen that the tensile strength, compression strength and shear strength are about 10% lower whereas moduli and bearing strength are nearly the same.

6 Element & Detail Level Processing

Many features like different T–joint configurations, skin-stringer panels, skin splice joint, spar splice joints representing select regions of a typical wing structure were fabricated as per the design requirement. Tools were split into smaller sizes and were sealed with modeling clay during infusion to prevent leakage at the edges. Infusion strategy like location of resin port, placement of distribution medium, location of vacuum line etc. was finalized using the data from coupon level.

Figures 13 to 15 show the T-joint, skin splice and spar splice joints respectively. These components were qualified using NDE and subsequently tested for design ultimate load successfully thus proving the process adopted.

7 Sub Component Level Processing

At the sub component level, the scalability of the processing technology was tested. A full-scale wing test box was the target structure mainly consisting of cocured top skin with stringers and cocured bottom skin with spars, ribs and stringers. Both top and bottom skins were proposed to be fastened at spar and rib locations. The objective was to prove the capability of VERITy process on a large scaled box structure in order to get adequate confidence on manufacturing full scale composite components. Requirements of tooling increased many fold catering for spars, ribs and stringers. Innovative infusion strategy was adopted wherein both parallel and series infusion was employed at different regions of the box. Parts were qualified using NDE and subsequently tested for design ultimate load successfully. The culmination of testing program paved the way for the mainline wing program. Figures 16 to 18 shows the CAD model, co-cured top skin and co-cured bottom skin with NDE evaluation.

NDE: A non destructive evaluation method of qualification of composite component by ultrasonic scanning process thermography, radiology etc.

Some of the key aspects that have resulted in the success are the innovative tooling concepts developed and the novel fibre optic based flow sensor system developed. Furthermore an automated resin infusion system was also developed. However, these are beyond the present scope of this paper.

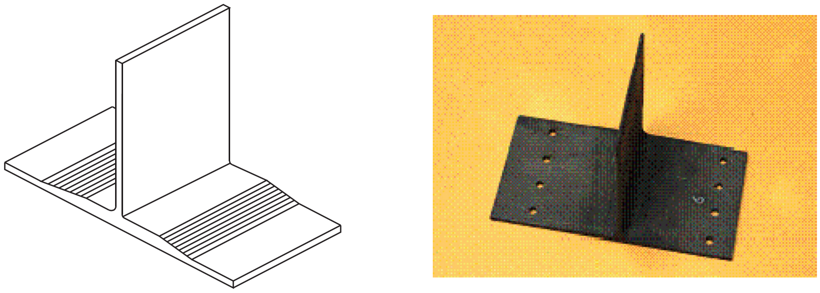


Figure 13: Schematic configuration & photograph of a typical T-Pull Specimen.

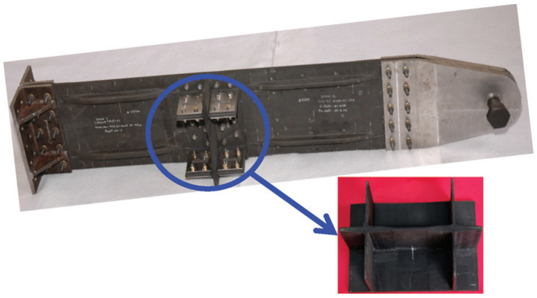


Figure 14: Skin splice joint with center splice rib.

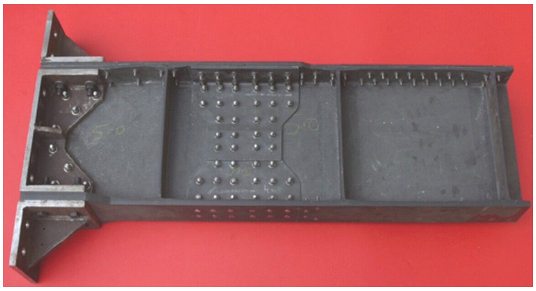


Figure 15: Spar splice joint.

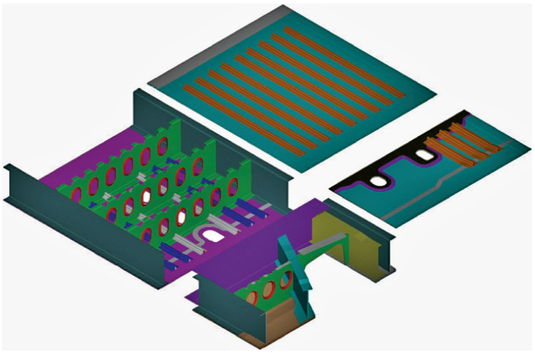


Figure 16: Model of wing test box.

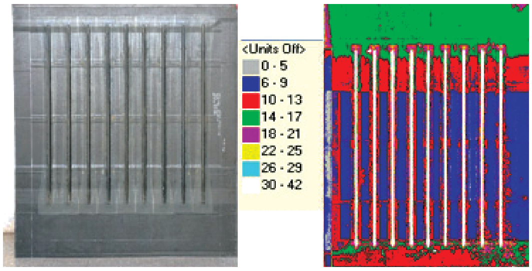


Figure 17: Top skin with C scan plot.

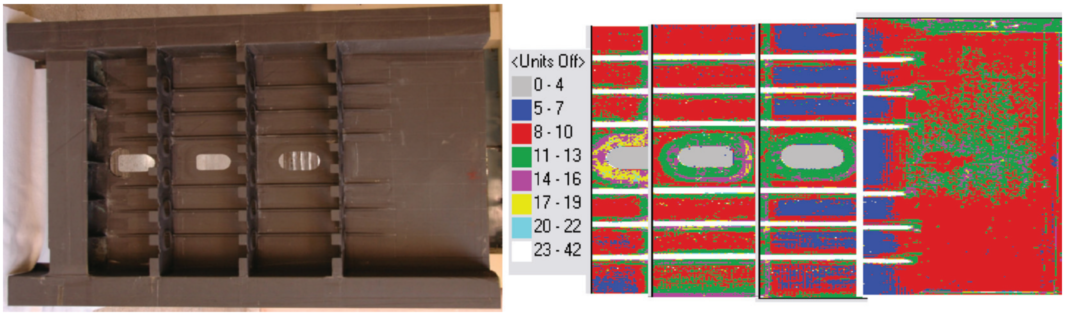


Figure 18: Co-cured bottom skin with C scan plot.

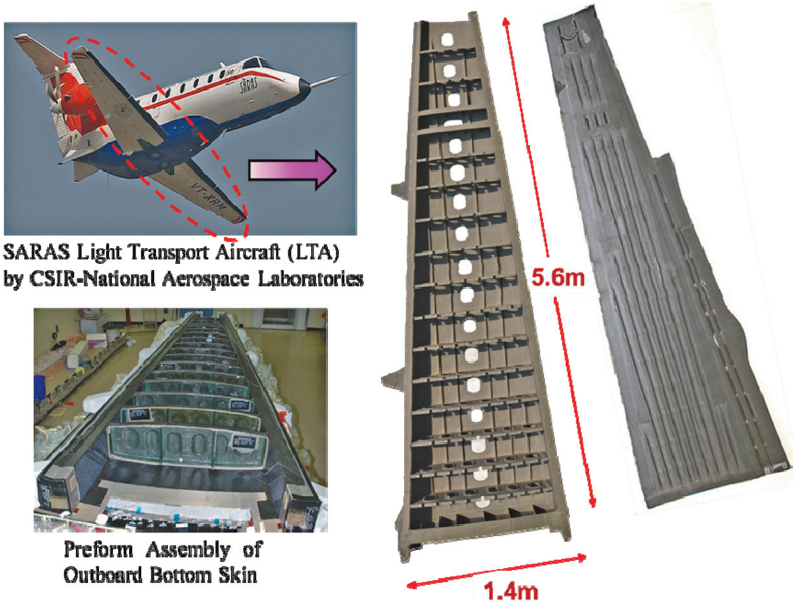


Figure 19: Co-cured bottom & top skin.

8 Component Level

The scaling up of technology from sub-component level to component level was not an easy task. The process parameters and technologies developed for the wing test box were reviewed based on the NDE results, dimensional inspection and tooling etc. and necessary corrections were made so that the manufacturing of wing components could be taken up. The outboard and inboard co-cured skins components were fabricated. The outboard top skin consists of 12 hat type stringers, 23 'T' type stringer co-cured with skin, having size

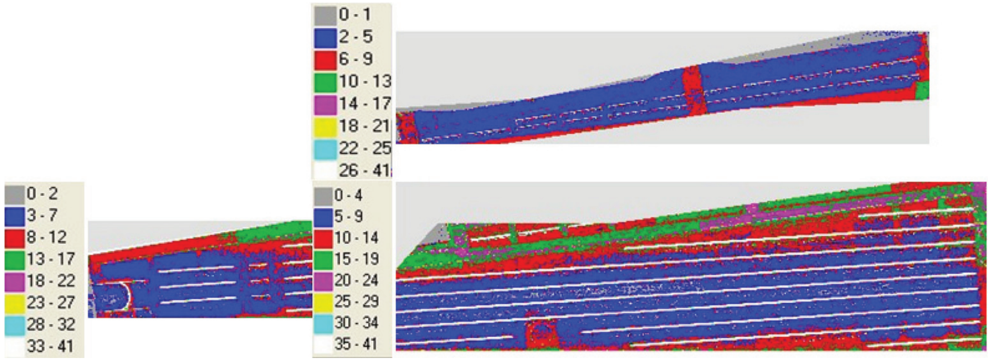


Figure 20: C-scan image of cocured top skin.

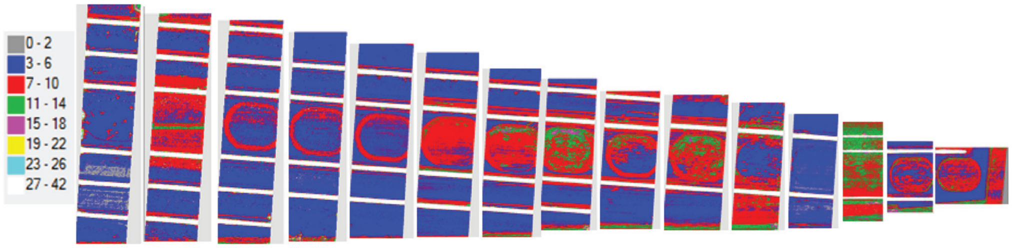


Figure 21: C-scan image of skin portion of cocured bottom skin.

of about 5.6 m length × 1.7 m width at root and 0.7 m width at tip. The thickness is varying from 1.36 mm to 8.16 mm. The size of the co-cured bottom skin is 5.6 m length × 1.4 m width at root and 0.6 m width at tip. The thickness is varying from 1.36 mm to 22 mm. This co-cured skin consists of skin, 31 hat type stringers and 3 'T' type stringers 17 ribs, 2 spars (front spar & rear spar) 97 gussets and 3 brackets. The challenge with the VERITy process was to wet the fibre bundles in the root area where the thickness was 20.4 mm. In addition to this the component had spars, ribs, stringers and gussets making the infusion involved. Parallel and sequential infusions were employed to realize the component. Similarly the inboard center top and bottom skins were co-cured with number of substructures. All these co-cured components were fabricated successfully. Ultrasonic C-scan showed that majority regions had consolidated as per requirements laid down. Fine tuning of process parameters and tooling is envisaged to iron out the higher porosity seen locally at select areas. Figure 19 shows the outboard top and bottom skin of SARAS aircraft wing. In the bottom structure nearly 300 parts are cured in one shot! Due to complex geometry, the ultrasonic inspection was carried out in many segments. Figure 20 shows the c-scan image of top skin and Figure 21 shows the c-scan image of portion of bottom skin.

9 Conclusions

CSIR-NAL has developed the technology from a holistic perspective and at multiple scales so as to understand the science and develop the technology it demands. The infusion technology was developed from coupon level to component level by carrying out experiments and necessary qualification testing at each level to understand the various challenging technical issues. The process was developed using building block approach and technology readiness levels were pushed from TRL 1 rating to TRL 8. The VERITy process has matured enough to realize the full scale SARAS composite wing components. The primary benefit of this technology development is a cost saving of 18% as compared to the prepreg/autoclave moulding technology. Other benefits include large scale integration and shorter assembly time.

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