Manufacturing Control

Certification and standards for composite material

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Abstract
As a master’s thesis in mechanical engineering at Luleå University of Technology this pre study for a future fan structure made of composite material has been done. The work has been carried out at Volvo Aero Corporation in Trollhättan.

This thesis covers three main areas; the today’s metal manufacturing and lessons and experiences that can be transferred to future composite manufacturing. The second part concerns the supply of suitable trade standards for composite manufacturing and, the third part investigates if there are special governmental requirements for composite material in the fan structure application.

The metal manufacturing of today is based on the same basic book of rules as a future composite product would have to be based. This leads to the conclusion that most of the basic safety and quality thinking applied today will be useful in the future. Of course a change in material will lead to changes in the production control procedures such as raw material acceptance testing and quality control of finished product.

Concerning trade standards the standards available reflects the stage in development which the composite material is in. The vast majority of the standards available from the major internationally used standard systems addresses basic material property testing of simple geometries and little has been found considering more realistic products.

The governmental certification rules studied is the American FAR regulations. The regulations mention only a few things especially for composite manufacturing and use. The main thing emphasized regarding composites, or other new materials is; if there is not long experience in using, designing and simulating the chosen material, extensive testing is required.
Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>DT</td>
<td>Destructive testing</td>
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<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
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<td>FAR</td>
<td>Federal Aviation Regulations</td>
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<td>FRP</td>
<td>Fibre Reinforced Plastic</td>
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<td>IMC</td>
<td>Intermediate Case</td>
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<td>IOGV</td>
<td>Integrated Outlet Guide Vanes</td>
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<td>NDT</td>
<td>Non Destructive Testing</td>
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<td>OGV</td>
<td>Outlet Guide Vanes</td>
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<td>RR</td>
<td>Rolls Royce</td>
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<tr>
<td>RTM</td>
<td>Resin Transfer Moulding</td>
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<td>VAC</td>
<td>Volvo Aero Corporation</td>
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1 INTRODUCTION

This master thesis is the result of the final project needed to gain the Swedish university degree in civil engineering. The work corresponds to 20 university points and has been going on from August 2004 to February 2005. The thesis work has been performed under the division of Polymer Engineering at Luleå University of Technology. The work has been carried out at Volvo Aero Corporation in Trollhättan, Sweden.

1.1 BACKGROUND

As a preparation for the upcoming VITAL project a number of thesis workers/students have been assigned different tasks connected to the “world of composites”. The thesis works range from CAD/FEM modelling of composites to design strategy and production strategy.

The current study will try to answer three main questions;

- Which lessons can be learned and transferred from the metal manufacturing of today to the composite manufacturing of tomorrow?
- Are there sufficient trade standards for manufacturing of high performance aerospace products?
- Are there special governmental certification requirements for composites in structural jet engine components?

1.1.1 The Vital project

Volvo Aero Corporation, VAC, has up until today only manufactured their products from metallic materials, mostly Titanium and Aluminium. In the close future a large European project is launched called VITAL, in which VAC will take part. One of the objectives of VITAL is to promote and develop new applications for composite materials in aerospace applications. Starting in the beginning of 2005 VAC in cooperation with amongst others Fischer Aerospace will attempt to develop and manufacture a static jet engine structure from composite material within the VITAL project. The structure in mind is the IMC showing in the figure below.
Besides introducing composite material into the IMC the VITAL aims to integrate the outlet guide vanes into the IMC. At the present the guide vanes are non load carrying and separately mounted in front of the IMC struts. The guide vanes job is to redirect the oncoming air, which is rotating some due to the fan rotation, and make the air travel straight towards the rear of the engine passing the IMC struts on the way. Integrating the OGVs into the IMC would possibly reduce the weight but more importantly reduce the number of components in the engine. The figure below shows the difference between integrated OGVs and the present design on BR715.
1.1.2 Why composites in aerospace applications?

The reason for introducing composite materials into aerospace applications is of course the possibility of weight reduction which if achieved would reduce aircraft fuel consumption. The benefit of engine weight reduction goes beyond the engine alone, since as the engine looses weight the load carrying structures in the fuselage may be scaled down saving several times the weight “shaved” of the engine.

1.1.3 Composite materials, a short introduction

A composite material is a solid material consisting of two or more phases combined during manufacturing to form a material that in some way performs better than the constituents would in a specific situation. An example of a common composite is reinforced concrete which is not as brittle as the cement or corrodes as easy as the steel reinforcement would on its own. However, normally when speaking about composite materials it is a material consisting of fibrous reinforcement embedded in a polymeric material but composites exist in many different forms. Composites are typically sorted by what material forms the matrix, there are three main classes; Polymeric matrix, Ceramic matrix and Metal matrix composites. Although Metal and Ceramic matrix composites has found some applications certain difficulties associated with them has limited their use so far. The largest composite group then is naturally the Polymer matrix composites and it is divided into two groups; thermoplastic and thermosetting plastic. The major differences between these plastics are that thermoplastic materials can be remelted and thermosetting materials are permanently shaped after setting. Thermosetting plastics may suffer from softening when heated but it will never return to liquid state when the crosslinking process is completed, when heated enough thermosetting plastics are combusted.

The reinforcement exists in several forms, the most common is of course fibres but they exist in several forms, as single long fibres, long fibre bundles, chopped fibres, whiskers (extremely fine and short fibres), as fabric weaved from fibre bundles and so on. The reinforcement can be in other forms than fibres, microscopic discs and spheres but these are most common in ceramic and metallic composites. There are a wide variety of fibres such as carbon, glass boron, natural etc. why the fibres have these attractive properties, high strength etc, depends simply on the weakest ling theory. Make any material thin enough and the possibility of a critical defect in the material will decrease due to the fact that there is simply not room for defects in the material. Of interest for the VITAL project is mainly carbon fibres, carbon fibres gain their high strength from the high degree of strong covalent C-C bonds oriented in the fibres’ longitudinal direction.
For high performance applications of polymer composites, light weight and high strength/stiffness, continuous fibres combined with a suitable thermosetting polymer matrix material is the most common combination. In a carbon fibre based polymeric composite it is the fibre who contributes with the strength, the matrix material is simply there to keep the fibres in place and distribute the force between the fibres.

2 MANUFACTURING IN METALS

The first part of this thesis is about the metal manufacturing of today and what lessons and experiences that can be transferred to the world of composites.

2.1 STUDY OBJECT

The metal product chosen to be studied is the BR715 IMC. The selection is based on the fact that the IMC to be built within the VITAL project is similar in size and general layout as the BR715 IMC.

Figure 3: The BR715 engine

2.1.1 BR715 IMC

The IMC, InterMediate Case, is located behind the fan and its main objectives are to function as the front engine mount and as the front engine axle bearing housing.
Figure 4: The BR715 IMC

Included into the IMC is the splitter box which job is to split the air stream into bypass flow and core flow. The core flow is directed into the engine core and is compressed and used in the combustion, the bypass flow is just forced out the back of the engine contributing to the engine thrust with the speed gained from the fan. As seen in the figure above the struts in this IMC has no other job than to distribute force between the engine axle and the engine mounts. The aerodynamic shape of the struts is only to reduce losses resulting from drag.

2.2 MANUFACTURING OF THE BR715 IMC

The BR715 IMC manufactured today is made out of an alloy called Titanium 6/4 and is casted in one piece before machined to exact shape.

2.2.1 Quality-, and process governing documents

All material and casting process related demands including repair procedures are listed in a governing document. In this case the name of the document is **RQS C10X-4008**. The purpose of the RQS is to “define the component quality standard for material condition and associated manufacturing controls necessary to ensure that the engineering specifications are achieved”. The RQS is as shown in figure 5 and described in part 2.2.2 a result of the combined demands from customer, design/construction and economy.

The RQS more specifically lists:

- The material and component for which it is applicable.
- Flaw and term definitions
- Flaw allowables, specified for each zone of the IMC, (see 2.2.2)
- Component zone definitions. (zones, see 2.2.2)
- General requirements.
- NDT, methods, specifications references, requirements and zone depending limits for discovered defects. (see 2.2.2 and 2.2.4)
Repair and adjustment requirements and associated specifications references

Material specification: Rolls Royce has numerous materials and their properties specified. The material used for the BR715 IMC is a Titanium alloy with RR spec. nr **MSRR8670**. The specification lists:

- Specifications reference for inspection and testing procedures.
- Specifications reference for test laboratory approval and control procedures.
- Specifications reference for test piece manufacturing.
- Chemical composition and allowed intervals.
- Raw material production parameters, whether or not use of remelted stock is permissible, process atmosphere requirements, batch/melt traceability etc.
- Casting parameters, (for casting with this specified raw material), protective atmosphere requirements, annealing, HIP and cooling parameters etc.

When VAC and the casting subcontractor agree on a specific casting procedure, to meet the RQS demands, including all process parameters the parameters and process are frozen, which means that nothing should be changed from here on. After the product certification is finished changes in the production cycle might require partial or complete re-certification of the production cycle. The next step is that one, or more, complete detail(s) are manufactured according to specifications, see figure 5, and then first put through the RQS-specified testing plan and then submitted to extensive destructive testing aimed to ensure the validity of the RQS. The testing is specified in the **Component Approval Package** document named **CAP BRR 035**.

The CAP BRR 035 includes:

- Governing documents references and General Requirements for handling of test results, test specimens and radiographs etc.
- Cut-up procedure and test requirements in general.
- Residual stress-, Metallurgical- and mechanical test requirements.
- Target properties.

Hopefully the CAP result is positive and the production can be started. If not the casting procedure and/or the RQS have to be changed so either the casting begins to perform better or the “Go-No Go” demands in the RQS is raised to give a higher product quality on the expense of higher repair and rejection/scrap rate. If the number of rejected parts increases dramatically as a result of the requirement changes then the casting process probably will have to be altered anyway since the cost for rejected parts is very high. The figure below, figure 5, is a summary of the procedure described in this chapter.
2.2.2 Deciding tolerances, philosophy of today

In the design process, besides material selection, some sort of agreement between design, quality, economics, material and manufacturing areas will have to be made as shown in the left topmost square in figure 5. Decisions on suitable levels of tolerances for everything from geometry to maximum sizes for material inclusions have to be set. This is an iterative process and results in guidelines for component approval and component testing as well as suitable tolerances for the engineering/casting/machining drawings.
When it comes to stating the specific quality demands, pore/inclusion sizes, maximum crack densities, welding regulations, surface texture etc. the approach can be made from two main directions. Either the quality requirements are set very high, demanding extremely flaw free material and narrow tolerances resulting in extremely optimised high cost products, or certain levels of flaws are used as design input and compensated with larger safety margins. Larger margins will result in a product with better price, as repair and scrapping rates are lower, but at the same time the weight will be higher.

In the case of the BR715 IMC these two approaches are somewhat combined by dividing the IMC into zones. The zones, named A, B and C, are chosen depending on each areas criticality. Zone A being the most critical, including engine mounts etc. is given the highest quality demands and the most restrictive welding restrictions. Zone B and C respectively are associated with somewhat lower demands allowing more and larger inclusions/pores etc and the repair restrictions are more generous.

Table 1: Zone allowables, an example

<table>
<thead>
<tr>
<th>Discontinuity Type</th>
<th>Zone A</th>
<th>Zone B</th>
<th>Zone C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>¼&quot;</td>
<td>½&quot;</td>
<td>⅛&quot;</td>
</tr>
<tr>
<td>Gas Holes (isolated)</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Gas Holes (clustered)</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Gas Holes (scattered)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Foreign material, less dense</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Foreign material, more dense</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Shrinkage, Centerline</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Shrinkage, Cavity</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Shrinkage, Scattered</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

The table above shows a list for Go-No Go limits, (of general type normally found in quality governing documents), for flaws found with an unspecified inspection method in the different zones, the numbers in the table refers to internationally standardized sizes.

### 2.2.3 The casting process

The casting process used for the BR715 IMC is known by several different names, Investment casting, Precision casting and Lost wax casting. The starting point is the making of the wax, (plastic), core or pattern. The wax core is supposed to be as good a replica of the intended finished product as possible but with some slight alteration to compensate for metal shrinkage. For complex and high precision products like IMC:s major work efforts are made to achieve a perfect wax pattern all the way from the moulding to, when necessary, quite extensive repair and dimension adjustments of the pattern.
When the pattern is deemed OK, wax “pins” are attached which will form the metal feeding system in the finished mould. The finished pattern is then dipped several times in different ceramic powders or slurries with pauses, (up to days), for shell/layer solidification. The ceramic mould materials used have to fulfil different tasks.

The first layer(s) have two major objectives and the first is that it has to be very fine grained as it decides the surface roughness of the finished part. The second is that, especially when dealing with titanium, it must not contain too much loosely bonded oxygen, this as the highly reactive titanium will attract the oxygen forming a brittle \(\alpha\)-case/layer on the surface which later have to be removed. No titanium casting process results in 100% \(\alpha\)-case free products, but the less the better.

The outer layers are for mould stiffness and strength and are for large moulds often reinforced with metal wire and/or rods. When the mould is finished the wax core is removed, often by heating. The finished mould is thoroughly inspected for cracks and other sources for leakage and as far as possible according to dimension as well.

The casting is fully automated and performed under vacuum to avoid excessive \(\alpha\)-case forming. Filling time, gas evacuation holes and cooling rate are designed to give the best possible product with the least amount of \(\alpha\)-case and interior defects. The specific details around the casting procedure differ between the casting firms, and they are quite secretive about the specific parameters.

The next steps in the process are the back end operations. The operations includes, in order of execution:
- Mould removal, it is done mainly with water jet blasting and shot peening.
- Feeding system removal, often by manual grinding/cutting.
• HIP, Heat treatment under pressure to close interior flaws/pores.
• Chemical milling, The $\alpha$-case is removed by application of acid.
• NDT, may take place several times during the back end operations phase.
• Repairs, every unit require repairs of some sort.
• Measuring, verification of exact size and as a preparation for- (see next point).
• Machining of datum bosses who forms the points used for locating the detail in space during the continued processing.
• Delivery to VAC for further machining.

2.2.4 Quality control

In the development phase especially, but also during manufacturing, testing of the achieved properties is important. This even more so when it comes to aerospace products for which there are strict government regulations. Testing methods can roughly be divided into two groups, Non-Destructive Testing, NDT, and Destructive Testing, DT. In the product/manufacturing development phase there are often several reasons for the use of destructive testing methods as to determine the production parameters and verify important physical properties aimed for during the design process. The destructive testing may also be used to calibrate and verify methods and equipment used for non-destructive testing if the methods are performed parallel to each other. The goal for all testing is to gradually move away from DT towards NDT, reasons for this are of course the costs linked to full scale destructive testing and the obvious need to obtain products that can be delivered to paying customers.

For the BR715 IMC the testing methods and the respective procedures are as previously mentioned specified in the RQS C10X-4008. Volvo Aero Corporation has, with the RQS specified testing, to fulfil extensive Rolls Royce regulations stating everything from eyesight requirements for the testing operators to service interval for testing equipment. When testing is performed at/by a subcontractor VAC supplies test pieces with prefabricated flaws used to check testing equipment and personnel. The major techniques used are described below.

**Visual inspection**: Performed several times during the manufacturing process due to its low cost. There is of course limits to what defects can be detected this way but a trained eye may save money since the cost is lower the earlier a flaw is detected.

**Penetrant inspection**: Used to detect surface cracks etc. The object to be tested is lowered into a chemical bath that is designed to penetrate narrow cracks and holes extremely well. The object is then washed and exposed to a development chemical. When exposed to UV-light, cracks and holes emit a fluorescent light that can be detected visually.
Ultrasonic inspection: Used to detect interior flaws such as cracks and voids, gas holes etc, but also used to measure wall thickness when only one side of the material is accessible, (not restricted to one side access measurements). Several different techniques are available depending on the signal used and the transmitter-detector arrangement. In the simplest form testing is performed by transmitting a short high frequency, (~kHz-MHz), pulse through the specimen and measuring the transit time. The receiver may either be placed on the opposite side from the transmitter, trough thickness, or the transmitter can function as both source and receiver recording the reflected signal from the back surface or a flaw.

Radiographic inspection, (X-ray): A penetrating beam of radiation is “shot” through the test piece. As it passes through the test piece different sections, as well as any discontinuities, absorbs varying amounts of radiation the emerging beam varies in intensity depending upon existing flaws and thickness variations. A photographic film sensitive to the chosen radiation placed on the opposite side from the radiation source will show less absorbing areas, such as voids for example, as light “spots” on the radiograph and of course discontinuities with more/higher absorption as darker spots than the base/flawless material.

Dimension and position tolerances are checked using measuring machines. The measuring is either done by a specific CMM, Coordinate Measuring Machine, or in some cases in the machining stage but then the tool machine has to be certified as a measuring machine. Internal clearances for transmission shafts etc are often checked using simple Go-No Go gauges.

Hang on bars testing: Hang on bars are material test pieces manufactured/casted alongside, and often attached to, the actual detail. The test bars are removed and then often destructively tested to verify material properties without harming the actual product. Today the use of hang on bars has decreased since questions have been raised regarding the validity of the data gained from this type of testing. The background to these questions comes from the fact that the hang on bars almost always show better properties than the material extracted from the cut up of the actual part, this is probably due to that the hang on bars are able to cool more rapidly than the actual product since the bars are located on the products outer surface.

A short list of the tests/checks performed on present products is presented here.

- **External geometry:** tolerances for interfaces to other components and surfaces not connecting to other parts but nevertheless vital to the components function, aerodynamic surfaces and shapes for example. Radius and fillets for avoidance of stress concentrations and simplifying the casting operation.
- **Internal geometries:** shapes and surfaces not affecting aerodynamic efficiency but still vital to the function of the IMC, for example the shape and size of the cavity inside strut no 5, gearbox axle duct BR715 IMC.
• Surface texture/roughness.
• Chemical composition.
• Material properties: material microstructure, presence of pores, gas holes surface- and internal cracks, flow lines, HIP-sinks, cold shuts $\alpha$-case etc.
• Mechanical properties: tensile-, fatigue- hardness- and fire resistance testing etc.

2.2.5 Repairs

The casting process is not perfect, according to people involved in the casting almost all units require some repair before being cleared for delivery. Often the repair is performed by first removing the damaged material and then filling the “cut” by welding. After the repair the detail needs to be heat treated to release any residual stresses resulting from the welding. The repaired area is then re-inspected by the inspection method used to detect the original flaw to ensure that the repair is successful. As previously mentioned repairs are restricted, in for example the engine mounts welding is prohibited so those areas need to be ok from the beginning.

3 COMPOSITE MANUFACTURING

In this chapter composite manufacturing techniques and important factors and sources error in composite manufacturing are presented along with some useful production control methods. [1, 2, 3, 4]

3.1 MANUFACTURING METHODS, SOME EXAMPLES

For the manufacturing of high performance and close tolerance parts for aerospace applications many of the more commonly used manufacturing methods will be insufficient. The method most likely to be used for the VITAL project is Resin Transfer Moulding, RTM. RTM and its closest competitor, Prepreg lay up combined with autoclave curing, is presented below.

3.1.1 Prepreg Lay-up

Traditionally prepreg lay up combined with autoclave curing has been the most common for state of the art products as for example parts for formula one cars and fighter aircrafts. The prepreg lay up has the possibility to produce extremely high performance parts but has a drawback in the vast amount of work, mostly manual, that is required to cut and stack the pieces
of prepreg that will form the part. Furthermore the autoclave is an expensive piece of equipment, especially if the parts manufactured, and hence the autoclave, are large. The production starts with the cutting and stacking of the prepreg mat, the mat might contain either unidirectional fibres or some sort of weave. The prepreg is stacked in a predetermined order to achieve the desired component properties. The prepreg stack is placed in a shaped mould, or on a flat surface depending on shape, the stack is covered with a breather and a resin absorbing layer which will absorb excessive resin and air. The final step is to seal the stack in a vacuum bag and place it in the autoclave. Inside the autoclave the vacuum bag is connected to a “vacuum source” and the autoclave is pressurised and heated. Air entrapped in the stack and excessive resin is forced out of the stack resulting in a hopefully pore less composite with high fibre volume fraction.

3.1.2 Resin Transfer Moulding, RTM

Until now RTM has mostly been used for mid, to close tolerance manufacturing of composites made in somewhat larger series than usual for the prepreg lay up method described earlier. The method works as follows; a fibre preform or a stack of dry fibre mat is placed in a mould, resin is injected in the mould impregnation the reinforcement forcing out any air from the mould. The resin injection is often vacuum assisted in order to ensure totally void free material.

The fibre preforms are available in various types. The fibres/mats may be pre-impregnated with some sort of binder which renders possibility to pre shape the reinforcement, see the left side in the figure above, before actual impregnation and curing. A preforming method coming more and more into use is 3-D weaving which makes it possible to weave fibre preforms with quite complicated shape and still use continuous fibres thus offering attractive solutions for T-joints and flanges etc.
Another advantage of the 3-D technique is the ability to incorporate reinforcement fibres in the out of plane direction improving the properties in that direction. The out of plane properties is the most troublesome for ordinary composites made from stacks of ply or prepreg which have more or less totally matrix dominated out of plane properties.

3.2 IDENTIFICATION OF POTENTIAL PROBLEMS

Composites, how wonderful they might be, may suffer from disorders or flaws which conventional materials won’t. This can be a problem, but as long as the manufacturer is aware of these composite specific problems then serious mishaps can be avoided through systematic controls in, and after, production. For raw material such as fibres, resin and core material etc governmental demands exist concerning testing of material properties at delivery and pre-production. Some controls may be left to the material supplier but some in-house testing is nevertheless required. Generally some testing will have to be performed for every resin batch and fibre/weave roll.

3.2.1 Raw materials

**Fibres**: An example of a problem that fibres may suffer from is the fibre coating, sizing, which is usually added on the individual fibres. A change in the coating may change composite properties dramatically. Usually the fibres are coated to enhance the fibre-matrix bonding strength but this bonding strength is a design variable that has to be given a certain target window in which it should remain. This as the fibre-matrix interface is one of the most important factors determining impact toughness. Too good fibre-matrix interfacial shear strength will cause the impact failure mode to shift from severe delamination, (large energy absorption), to a brittle “all or nothing” failure, (low energy absorption). A too weak interface will result in lower tensile strength as the matrix ability to transfer loads to the fibres decreases. Further testing required by authorities includes tensile strength and modulus, density and fibre/bundle form and twist. A twisted fibre bundle will for example behave less stiff in the finished product than a perfectly aligned one.

**Matrix**: Assuming for example the RTM production process, certain things have to be kept under control. If for example the viscosity rises for some reason, the mould filling will be more difficult and the risk for voids higher. Viscosity change may occur due to problems in raw material storing or excessive storage time. Chemical composition is another important variable. The amount of functional groups for example has a strong influence on curing behaviour, achievable degree of cure and for the completed composite; load transfer abilities between fibres etc. Beside mentioned properties FAA recommended property testing includes gel time, cure Kinetics and rheology.
Preform/prepreg: Fibre preforms should be checked according to shape, and possibly also weighed to determine its quality. Even as a distorted preform might be inserted into the mould the “bending” required to make it fit might result in the reinforcement being misaligned in the finished part. The preform weight, together with other data, may be used to estimate the fibre volume fraction and even void content if the measurement is performed accurately enough. For prepreg material a combination of the properties checked for resin and fibres will have to be verified, fibre and matrix content, chemical composition of the resin etc. No geometrical defects are allowed such as wrinkles or waviness and the adhesion to the backing tape should be perfect without bubbles to assure successful assembly of the composite.

3.2.2 Processing/manufacturing

Since the properties of the composite are mainly created during the final manufacturing of the composite the manufacturing process has a large impact on the result.

Below some of the important parameters in RTM are listed along with descriptions of associated problems, [17]:

- **Constituent materials** from suppliers - affect laminate strength, stiffness, processability, porosity, surface finish.

- **Reinforcement materials production** (weaving, braiding, etc.) - affect laminate strength, stiffness due to fibre orientation, fibre damage, areal weight/fibre volume.

- **Reinforcement materials processing** (application of binders or tackifiers and other materials) – affect ability to form materials/define shapes, ability to form multiple layers simultaneously, permeability changes which affect ability to impregnate preform, could affect laminate structural properties if materials are incompatible with each other.

- Cutting and **stacking** of plies - affect orientation of materials or lay-up sequence which establishes structural properties, ply drop-offs within the component which define local fibre volumes.

- Forming of shapes/preforming - affect ply orientation, ply drop-offs, local fibre volumes.

- **Assembly of preforms/tooling** - affect ply/fibre orientation and alignment, ply drop-offs, fibre volumes, part geometry, ability to flow resin and impregnate preform.
• Liquid resin processing/cure parameters (time/temperature profile, vacuum, pressure, flow rate, viscosity of resin) - affect laminate porosity level, glass transition temperature (Tg), laminate surface finish quality.

• Demolding and tool cleaning (removing part from tooling) - affect laminate integrity due to possible delamination, surface finish (scratches, gouges).

• Tooling design and tooling materials selection (coefficient of thermal expansion, (CTE), considerations – affect tool life, part surface finish, part integrity, (which could be affected by CTE mismatch causing laminae damage), and processability.

For autoclave cured prepreg the main sources of variability are, [17]:

• Tooling or mould surface finish; poor surface finish will transfer to finished product.

• Tooling materials, density, and spacing of tools in the autoclave; more, denser tools closer together will act as a heat sink and affect degree of cure.

• Part geometry; the more complex the geometry the more difficult to achieve uniform consolidation and avoid wrinkling.

• Lay-up symmetry; non-symmetrical geometry and/or lay-up cause part warpage or springback.

• Material location and alignment tolerances; non-symmetrical lay-up causes part warpage.

• Bagging technique and bagging materials including bleeder materials and cauls, etc.; vacuum bagging material movement or restriction from complete contact against curing material (i.e., bridging) causes non-uniformity in material compaction and resin flow affecting the quality of the finished product.

• Number of interim debulk cycles and debulk time, temperature and pressure (vacuum); insufficient debulking causes thickness and surface finish variability as well as wrinkles in the finished part.
3.2.3 Finished product

Curing: The goal for the curing process is to reach 100% degree of cure. A lower degree of cure generally leads to lower tensile modulus, glass transition temperature and a decrease in thermal stability and chemical resistance for the matrix material. Factors influencing the degree of cure are amongst others resin chemical composition, curing time and temperature.

Delaminations: are cracks in the matrix between, or parallel to, reinforcement. The result is a decrease in the composites ability to carry load as the matrix primary job of distributing the load between the fibres is locally destroyed. In addition to this, a lowering in fatigue resistance might occur due to the fact that a crack is already present and the usually long time for crack initiation is vanished. Delaminations can appear as a result of fracturing and then due to interlaminar shearing. Delamination may also occur during manufacturing usually as a result of poor wetting of the reinforcement. Another source of delamination, and an almost certain one, is machining of composites, for example drilling. It is practically impossible to cut a hole through a composite without the formation of at least a small damaged/delaminated area around the hole.

Voids: are simply bubbles of air trapped inside the composite when the curing is done. Voids can appear as single bubbles or in groups and the severity depends on size and location. A void leads to a local stress magnification/concentration in the surrounding material. As said elsewhere voids can act as the starting point for further delamination.
Inclusions: Closely related to voids, inclusions are non-wanted particles, contaminations, embedded in the composite, and are introduced in the manufacturing stage. The problems related to inclusions depends on the type of inclusion, a soft weak material acts more or less as a void and a hard brittle one as a source for crack initiation and delamination. The size of the inclusion is of course important, most common is ordinary dust carried by air and it should of course be kept to a minimum as a layer of dust on the preform inhibits fibre-matrix bonding ability. Larger inclusions may, if large enough, distort the reinforcement. A “perfect” inclusion, with properties suiting the matrix might not cause many problems if the inclusion bonds to the matrix and otherwise have the right properties. But all and all inclusions should be avoided and the simplest way to do that is to keep the production environment clean and airborne dust quantity to a minimum.

Fibre volume fraction: Disturbances in production may result in local fibre volume fraction variations. This most often appear where the fibres are forced to make sharp turns, small radii, or around holes introduced in the moulding. The result is usually a local matrix enrichment that locally decreases the load carrying ability and thus increases damage sensibility. Another possibility is to get a local matrix shortage i.e. fibres touching each other after the matrix material has been injected and cured. Touching fibres may also be a result of pre matrix introduction bending of the reinforcement but also of poor fibre wetting by the matrix. The result of touching fibres is a, however small, delaminated area.

Reinforcement distortion: Since the composites strength and stiffness is so closely related to the fibre properties, fibre alignment becomes very important. However small the misalignment might be it immediately results in some additional interlaminar shear stresses when the laminate is strained. The stresses are of course small when the misalignment is small. Ply, or fibre, waviness causes additional fibre-matrix interface shear stresses when the composite is strained.

Core shape and location: Foam/honeycomb core shape and location and core to lamina adhesion are things that might adversely affect the strength and stiffness if there are problems with them.

Micro cracking: is most common as a result of service use, but some micro cracking might appear when curing the composite as a result of thermal stressing. This often depends on the usually large difference in coefficient of thermal expansion between the matrix and the fibres. The in service micro cracking depends mainly on the matrix starting to break away from fibres not oriented in the direction of strain. As the ultimate strength of a laminate in tension is governed by the strength of the fibres, these resin micro-cracks do not immediately reduce the ultimate properties of the laminate. However, in an environment such as water or moist air, the micro-cracked laminate will absorb considerably more water than an uncracked laminate.
Chemical damage: is more common in use than in manufacturing. This kind of damages includes water absorption and attack by other chemicals as fuel, oil and antifreeze. As long as the matrix raw material is stored under the appropriate conditions and eventual machining coolant and penetrant testing fluids are selected to suit the composite constituents the potential chemical degradation will occur during the details service life. Water absorption leads to a lowering in Tg for the matrix and the result is among others deteriorated high temperature properties, increase in weight, moisture attack on the resin and fibre sizing agents, loss of stiffness and, with time an eventual drop in ultimate properties. Other chemicals may cause problems like destroyed fibre-matrix interface and surface cracking. Protective coating will help relieve these problems but the best way, when possible, is to choose materials that will not be affected by the service environment.

3.3 FLAW DETECTION METHODS

Finding interior defects or irregularities in composite material can be done either destructively or non destructive. As mentioned before economic demands require that testing moves more and more from destructive to non destructive methods. Generally most of the techniques used for metal quality control may be used for composite control as well, adjustments to the hardware and procedures will often be necessary though. In figure 8 below some of the most common testing techniques are compared to each other. The chance of flaw detection increases if several techniques are used, this since they all have their strong and weak sides, and for aerospace products it is often required that several test methods are used to ensure product quality.

<table>
<thead>
<tr>
<th></th>
<th>Visual</th>
<th>Tap Test</th>
<th>A-Scan</th>
<th>C-Scan</th>
<th>X-Rays</th>
<th>Thermal</th>
<th>Dye Penet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Delays</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>NA</td>
</tr>
<tr>
<td>Deep Delays</td>
<td>NA</td>
<td>C</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>NA</td>
</tr>
<tr>
<td>Full Diebond</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>NA</td>
</tr>
<tr>
<td>Missing Diebond</td>
<td>NA</td>
<td>C</td>
<td>C</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Core Damage</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>NA</td>
</tr>
<tr>
<td>Inclusions</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>NA</td>
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<tr>
<td>Porosity</td>
<td>B</td>
<td>NA</td>
<td>B</td>
<td>A</td>
<td>NA</td>
<td>NA</td>
<td>B</td>
</tr>
<tr>
<td>Void</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Backing Film</td>
<td>NA</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>NA</td>
</tr>
<tr>
<td>Edge Damage</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>Heat Damage</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>NA</td>
<td>B</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Severe Impact</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>C</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Medium Impact</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>NA</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Minor Impact</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>NA</td>
<td>C</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Uneven Bendline</td>
<td>C</td>
<td>NA</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>NA</td>
</tr>
<tr>
<td>Weak Bond</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Water in Core</td>
<td>NA</td>
<td>E</td>
<td>C</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>NA</td>
</tr>
</tbody>
</table>

Figure 8: Abilities of testing methods, A=Good, B=medium, C=not so good. From http://www.netcomposites.com/education.asp?sequence=68 date 040927
**Visual inspection:** is by far the cheapest to perform but have some obvious limitations. Defects detectable by vision are by nature those accessible from the parts outer surface. If visual inspection is required in the parts production governing documents inspection personnel will have to have formal training and the inspection have to be performed in a certain environment with specified light conditions etc.

**Tap test:** is in its simplest form no more expensive than visual inspection. The idea is to listen to the sonic response that is the result of tapping the tested material with a solid hard object, a coin for example. If the response is a clear “tone” it is an OK sign, but if the response is a dull “thump” it is a sign of damage. As mentioned the simplest form of tap testing is performed using nothing other than the hand and ear of the testing person, but several mechanised techniques for tap testing exist utilising exact impact force/energy, computer analysed response and of course simplified methods for recording the test results.

**Ultrasonic inspection:** Overall ultrasonic techniques are the most widely used NDT method for advanced composites. It has large potential to detect delaminations, voids, porosity, inclusions and in some cases other flaws like broken or distorted reinforcement. As mentioned earlier ultrasonics are all about studying the signal attenuation of a high frequency pulse passing through the test piece. Several types of ultrasonic techniques exists, the A-scan and C-scan listed in the figure above for example.

The **A-scan technique** is perhaps the simplest method of presenting ultrasonic information. The signals received by the transducer are rectified and displayed as the vertical deflection on an oscilloscope screen. An A-scan comprises a series of spikes whose position along the horizontal time axis can be calibrated in terms of depth in the sample under test so that the depth of a reflector can be measured. The amplitude of each echo gives some indication of the size and nature of the reflector, which might be a defect or a specimen boundary.

The **C-scan technique**; In this type of imaging a more complex scanning system is used such that the transducer is scanned in a plane parallel to the sample in a rectilinear raster pattern, see picture below. In older systems a recorder pen was often mechanically coupled to the transducer manipulator so that the pen reproduces the scanning pattern. However, modern computer controlled systems monitor the position of the transducer and store this with the ultrasonic data for that position.

The C-scan does not have the ability to determine at what depth in the material the damage is, but some c-scan computer software are able to be programmed to ignore small thickness variations that otherwise might be interpreted as interior defects. In appendix 1 it is described an ultrasonic inspection test performed at VAC using existing equipment.
**X-ray or radiographic inspection:** as previously mentioned x-ray inspection is performed by shooting a beam of radiation through the test piece and detecting the residual radiation emitted on the back side of the test piece. The difference in radiation intensity is due to that X-rays are attenuated by a mechanism involving changes in the energy states of electrons in the X-ray beam. X-radiography therefore relies on detecting changes in the electron density within the material along the length of the beam. The difference in intensity may either be used to develop suitable photographic film or by more recent techniques develop an instant computerized image. As neither delaminations nor disbonds affect that electron distribution significantly, these two defects are virtually invisible to X-rays.

**Thermography:** Thermal response techniques has during recent years come more and more into use as a NDT technique for composite materials. There are several types of thermographic methods but they all have in common that the physical response to variations in temperature of the test piece is observed and measured in some way. Some thermography techniques are described shortly below.

**Thermal Imaging:** Standard thermal imaging methods can be used passively to view structures as they heat up or cool down. A good example of this is the detection of water in honeycomb aircraft structures just after landing, as they warm up. The presence of water changes the local heat capacity of the structure and can be seen on the image as a cooler region.

**Pulsed Thermography:** Pulsed thermography has been available for over 10 years and is an active method where the structure is heated by a short-duration thermal pulse from flash lamps. The temperature profile of the surface is then monitored as a function of time. The principle is that the heat diffuses less well through a thermal barrier such as a delamination and the
surface remains at a higher temperature above a defect of this type. Eventually the heat diffuses around the defect and the surface reaches an equilibrium state again. It is possible to use the temperature-time profile to determine the approximate depth of a defect.

**Lock-in Thermography**: this is another active method but instead of a single pulse of heat, the heat source is modulated continuously at a single frequency of modulation. Due to the periodic fluctuations of temperature it is possible to model the behaviour of the structure as if the diffusion of heat obeyed the wave equation. This introduces the concept of phase. There is a phase lag between the source temperature and the surface temperature of the specimen and this will depend on the structure and its thermal properties. Hence, as well as having actual amplitude data, there is phase information that should give further insights into the condition of the structure. One immediate advantage is that the phase is unaffected by the local surface emissivity variations that cause problems with amplitude measurements.

**Tomography**: a non-destructive X-ray technique which can be used for inspection and evaluation of composite structural components. It is also known as computerized axial tomography (CAT Scanning) and is based on the principle that radiation directed through a given volume of material will be differentially absorbed by the material according to its mass absorption and physical density. CT images produced are of cross-sectional slices through the object showing the internal distribution of the X-ray-attenuating properties of the material. From these sophisticated radiation absorption measurements the material can be characterized. CAT-scan is still a young technique for composite control, it shows good results but is quite time consuming and requires quite expensive equipment.

### 4 STANDARDS

If there were no standards, it would soon be noticed. Standards make an enormous contribution to most aspects of the daily life of most humans, although very often that contribution is invisible. But for example, purchasers or users of products would soon notice when they turn out to be of poor quality, do not fit, are incompatible with equipment already existing or are unreliable or dangerous. When products meet user expectations, the user tends to take this for granted. People are usually unaware of the role played by standards in raising levels of quality, safety, reliability, efficiency and interchangeability.

When the large majority of products or services in a particular business or industry sector conform to international standards, a state of industry-wide standardization can be said to exist. This is achieved through consensus agreements between national delegations representing all the economic stakeholders concerned - suppliers, users, government regulators and other interest groups, such as consumers. They agree on specifications and criteria to be applied consistently in the classification of materials, in the manufacture and supply of products, in testing and analysis, in terminology and in the provision of services. In this way, international standards provide
a reference framework, or a common technological language, between suppliers and their customers that facilitates trade and the transfer of technology. For businesses, the widespread adoption of international standards means that suppliers can base the development of their products and services on specifications that have wide acceptance in their sectors. This, in turn, means that businesses using international standards are increasingly free to compete on many more markets around the world.

When it comes to standards in aerospace industry the role the standards play is more a quality assurance tool. The standards are used as a book of rules to as how material data gathering, product development and testing etc should be performed to assure reliable and comparable results and thus resulting in a simplified certification process, (see further on certification demands in chapter 5).

4.1 VOLVO CORPORATE STANDARDS

The Volvo corporate standard system is maintained to assure a high and even quality level independent of location and personal judgement by personnel performing manufacturing, testing or construction etc.

4.1.1 Composite related Volvo standards

The Volvo corporate standard system includes a very small number of standards dealing directly with composite material. The composite related standards that may be found are mainly dealing with low-quality GFRP bodywork for heavy trucks. Some regulations for storage and handling of polymeric materials and their constituents, pre-polymers and curing agents, are available but for a limited number of materials which would imply that material selection decide whether or not these standards will have to be considered.

4.2 EXTERNAL STANDARD SYSTEMS, OVERVIEW

Around the world several national en regional standard systems exist. In the modern world of today, with a more and more international trade the former national standard systems are joined to larger regional systems which in their turn are more or less homologised against other similar regional systems in other parts of the world. In this part the two major standard organisations are presented, ISO (European) and ASTM (USA) alongside with the, in the context, newly formed AECMA (European). Furthermore a short remark on the standard use at VAC today is made.

4.2.1 ISO

ISO, International Organization for Standardization. ISO is a network of the national standards institutes of 146 countries. ISO is a non-governmental
organization and its members are not, as is the case in the United Nations system, delegations of national governments. Nevertheless, ISO occupies a special position between the public and private sectors. This is because, on the one hand, many of its member institutes are part of the governmental structure of their countries, or are mandated by their government. On the other hand, other members have their roots uniquely in the private sector, having been set up by national partnerships of industry associations.

### 4.2.2 ASTM

ASTM International, originally known as the American Society for Testing and Materials (ASTM), was formed over a century ago, when a group of engineers and scientists got together to address frequent rail breaks in the growing railroad industry. Their work led to standardization on the steel used in rail construction, ultimately improving railroad safety for the public. As the century progressed and new industrial, governmental and environmental developments created new standardization requirements. Now ASTM International is one of the largest voluntary standards development organizations in the world—a source for technical standards for materials, products, systems, and services. ASTM International standards have an important role in the information infrastructure that guides design, manufacturing and trade in the global economy according to themselves.

### 4.2.3 AECMA

The European Association of Aerospace Industries, AECMA, represents the aerospace industry in Europe in all matters of common interest on the level of aircraft/systems, engines, equipment and components. Its objective is to enhance the competitive development of the whole sector. A suborganisation of AECMA is AECMA-STAN and its purposes are:

- Establish, develop and maintain standards requested by the European Aerospace Industry,
- Ensure the standardization process is operated in a business-like manner,
- Promote the world-wide recognition and acceptance of AECMA standards,
- AECMA-STAN also holds a sole provider status for European aerospace standards (EN) established via a protocol with CEN, the European Committee for Standardization

### 4.2.4 Others

Most countries maintain their own standard systems, but these “local” systems are either phased out or homologised with the major international systems as a result of the needs created by the increasing globalisation. If one of the national systems is to be mentioned it is the English BSI-system which is quite extensive. The Swedish SIS is fully ISO-homologised.
4.2.5 Similarities and connections

All three of AECMA, ISO and ASTM systems share some of their respective content, and cross references sometimes exist. Especially in ASTM standards abstracts remarks often can be found whether or not similar ISO standards exist and if so their number.

4.2.6 Standards used by VAC today

Quite often VAC’s use of standards is governed by the requirements and demands of the customer. Besides the respective customers corporate standards the origin of the customer more or less decides the standard system to be used. American companies usually prefer the ASTM system and European subsequently prefers the ISO or AECMA systems. For material related questions VAC uses mostly ASTM when no exterior demands state otherwise and it is due to the wide variety of available ASTM material standards. However, VAC is more and more moving towards using AECMA since it is an aerospace-specific standard system used by most major aerospace companies in Europe.

4.3 EXISTING STANDARDS FOR COMPOSITE PRODUCT CONTROL

In this section an example of a simplified chain of requirements is presented and suitable standards for the examination of the properties mentioned in the tree are listed. Furthermore thin areas, areas lacking suitable standards, are identified. Generally one may say that there is no lack of standards after a first glance, the ASTM online catalogue alone covers about 12000 standards. But when specifying the search to standards dealing exclusively with raw materials, production and post production/acceptance testing of Carbon Fibre Reinforced Plastics the number drops rapidly. [8, 12, 14, 15, 16, 17]
4.3.1 Standards concerning testing and methods for testing

In this section an effort to identify suitable standards for the testing and quality control of a produced composite product is made. No examination of standards concerning material data gathering for the product development phase is made. The above figure shows an example of a very simplified chain of requirements. The chain describes where the demands originate and how they are transferred down the ladder. The areas “Raw materials”, “Completed Composite” and “Geometry” in their turn consists of several sub requirements which are further described below with specific standards pinned to each area. For the resulting composite problem related to a problem in areas mentioned in this part see chapter 3.2.3 for additional explanation.

**Raw material, properties verification**

The area of raw materials has in this investigation been limited to fibre, matrix, or resin, and core material, for use in sandwich constructions. Since the possibility for repair or adjustment of a composite material is extremely limited after the curing of the resin is complete the aspect of raw material testing, or control, will have new and wider meaning than for metals. For metals used in casting the main thing that is checked previous to the actual casting is the chemical composition, the result of the casting process is then mainly depending on the casting process parameters. Eventual irregularities, flaws, is characterized and repaired later on.
In the figure above some important properties of the constituents are shown and how they can be combined to form important properties of an eventual preform. Below suitable standards for each individual constituent are listed and explained.

**Fibre**

**Table 2: Properties and related standards for fibres**

<table>
<thead>
<tr>
<th>Fiber Property</th>
<th>Test Condition</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form</td>
<td>N/A</td>
<td>ASTM E1309</td>
</tr>
<tr>
<td>Twist</td>
<td>N/A</td>
<td>Any agreed method</td>
</tr>
<tr>
<td>Size Content</td>
<td>Ambient</td>
<td>ASTM D4018</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>RTD</td>
<td>ASTM D4018</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>RTD</td>
<td>ASTM D4018</td>
</tr>
<tr>
<td>Density</td>
<td>RTD</td>
<td>ASTM D3800</td>
</tr>
</tbody>
</table>

The table above mentions some testing procedures and associated standards which are recommended by DOT and FAA for acceptance testing of fibres and multifilaments intended for use in high performance aerospace applications.

Form means the roundness of individual fibres and it is of importance due to the varying material properties depending on fibre-matrix interface. Very oval fibres yields larger interface area in proportion to fibre cross sectional area and this may affect the failure behaviour of the composite.

Twist is concerning the alignment of individual fibres in relation to the longitudinal axis of a fibre bundle. A bundle with high degree of alignment will act stiffer when strained than a bundle consisting of poorly aligned fibres. Poorly aligned fibres might also increase the chance of micro
cracking. Since no specific test method/standard is listed the manufacturer and the FAA can agree on any method that fulfils the purpose.

Sizing/coating content and composition will have to be verified by Chemical analysis and additional methods. The coating is very important to the failure behaviour of the composite. Speaking in general terms it would be possible to, for some ideal fibre-matrix systems, vary the failure behaviour from 100% brittle to almost “metal like” plastic just by altering the sizing type and content.

Tensile modulus and Strength is natural things to check. Fibre strength and stiffness has direct impact on composite properties, low fibre strength and stiffness will result in low composite strength and stiffness.

Fibre density should be checked mostly to make sure that all other properties are correct since incorrect density may indicate problems on other fronts.

**Resin/ Matrix material**

<table>
<thead>
<tr>
<th>Table 3: Properties and related standards for the resin material</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resin Property</strong></td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>Viscosity</td>
</tr>
<tr>
<td>Gel Time</td>
</tr>
<tr>
<td>IR</td>
</tr>
<tr>
<td>HPLC (ingredient ratios)</td>
</tr>
<tr>
<td>Cure Kinetics</td>
</tr>
<tr>
<td>Rheology</td>
</tr>
</tbody>
</table>

The above table shows recommended tests and associated standards for the resin material.

Viscosity is checked to amongst others assure problem free injection when for example RTM is used to manufacture the composite. It may also indicate if the resin has been stored too long if the viscosity is higher than normal. Viscosity and Gel time will also give a quick verification of the mixing ratio between hardener and pre-polymer which will affect the time needed in the tool for the detail to solidify. Viscosity might for example be tested according to AECMA standard prEN 6043.

Infrared Spectrophotometry and High-Pressure Liquid Chromatography are used to determine the chemical composition of the resin, such as the amount of functional groups and other important factors. For the HPLC there are no specified standard but standards for that method exists that may be modified to fit the testing of the matrix, for example ASTM D6579-00.
Testing the Cure kinetics will result in a curve describing the hardening/setting process against time. This to make sure that the resin will perform according to process specifications.

Rheology examination is made to determine deformation against time for the matrix material, again to give information about the composition of the material.

**Prepreg and dry fibre preforms**

*Table 4: Properties and related standards for prepreg and preform material*

<table>
<thead>
<tr>
<th>Uncured Prepreg Property</th>
<th>Test Condition</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Content, areal weight</td>
<td>SACMA SRM 23</td>
<td></td>
</tr>
<tr>
<td>Resin Content, % by weight</td>
<td>ASTM D 3529</td>
<td>SACMA SRM 23</td>
</tr>
<tr>
<td>Insoluble Content</td>
<td>ASTM D 3529</td>
<td></td>
</tr>
<tr>
<td>Volatile Content, % by weight</td>
<td>ASTM D 3530</td>
<td></td>
</tr>
<tr>
<td>Flow, % by weight</td>
<td>ASTM D 3551</td>
<td>SACMA SRM 22</td>
</tr>
<tr>
<td>Gel Time, minutes</td>
<td>ASTM D 3532</td>
<td></td>
</tr>
<tr>
<td>HPLC (ingredient ratios)</td>
<td>SACMA SRM 20</td>
<td></td>
</tr>
<tr>
<td>IR (Ingredients Chemical Signature)</td>
<td>RTD</td>
<td>ASTM E 1252</td>
</tr>
<tr>
<td>Chemical Reactivity and Degree of Advancement via DSC</td>
<td>ASTM E 1356</td>
<td>ASTM D 3418</td>
</tr>
<tr>
<td>Tack</td>
<td>RTD</td>
<td>Any agreed method</td>
</tr>
<tr>
<td>Drape</td>
<td>RTD</td>
<td>Any agreed method</td>
</tr>
</tbody>
</table>

The above listed standards are applied to ensure the quality of the prepreg material. Most of the tests are mentioned in previous sections but some require some additional description.

Fibre and Resin content are measured to assure proper composite properties as for example strength and stiffness will suffer if fibre content is too low and ply to ply adhesion will be jeopardized if resin content is too low.

Differential Scanning Calorimetry, DSC, is used to for example determine degree of cure but also water content after environmental exposure.

For dry fibre preforms this investigation has resulted in no applicable standards, but if preforms are used, it will be necessary to develop standards for the inspection of such material.
Core material

*Table 5: Properties and related standards for core material*

<table>
<thead>
<tr>
<th>Core property</th>
<th>Test method (ASTM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determination of compressive strength and modulus of sandwich cores</td>
<td>C365-03</td>
</tr>
<tr>
<td>Determination of thickness for flat sandwich cores</td>
<td>C366-99</td>
</tr>
<tr>
<td>Determination of the density of sandwich construction core materials.</td>
<td>C271-99</td>
</tr>
</tbody>
</table>

The above mentioned core related testing methods are used to verify some of the important properties of the core material.

Compressive strength is of importance as the core often is subjected to compressive stresses when the composite as a whole is subjected to bending.

Thickness is of importance as the core thickness will affect the total thickness and thus also strength and stiffness.

Control of density may be performed to determine if water or other non wanted substances has penetrated the core material.
Material properties verification, finished composite

As shown in the above figure, composites as well as other materials may suffer from local defects and/or defects that influence the whole part. The raw materials testing mentioned earlier should reduce the risk for defects on component level but still the risk for local defects remain and is mostly depending on processing/manufacturing. This section will describe examples of tests and standards useful for determining production outcome.
The following table contains material tests recommended by the FAA.

*Table 6: Properties and related standards for completed composite material*

<table>
<thead>
<tr>
<th>Material property</th>
<th>Test method /Standard example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Void content</td>
<td>ASTM D2734-94</td>
</tr>
<tr>
<td>Fibre volume content</td>
<td>ASTM D3171-99</td>
</tr>
<tr>
<td>Core adhesion</td>
<td>No specific method available (see general methods below)</td>
</tr>
<tr>
<td>Delaminations</td>
<td>No specific method available (see general methods below)</td>
</tr>
<tr>
<td>Degree of cure (depending on situation measurement of Tg might be the best method to determine degree of cure)</td>
<td>ISO 12114:1997 (Tg determination) AECMA prEN 6032 (Tg determination)</td>
</tr>
<tr>
<td>Fibre orientation</td>
<td>No specific method available (see general methods below)</td>
</tr>
<tr>
<td>General material discontinuities detection Non Destructive Testing techniques</td>
<td>ASTM E1495-02 (ultrasonic) ASTM E2192-02 (ultrasonic) ASTM E2104-01 (radiography)</td>
</tr>
</tbody>
</table>

All of the material properties mentioned in the table above have in common that they will weaken the material in some way if there are problems with one or more of these. Most of the methods above are destructive methods which lead to the fact that they are most suitable for testing of hang on bars, simple panels manufactured parallel to the main product. For testing on the actual product Non Destructive Testing techniques are often the only option. The testing of hang on bars might be used to verify the process outcome and as additional verification of the raw material quality. Below some additional tests and standards for the testing of hang on bars are listed.

*Table 7: Properties and related standards suitable for hang on bar testing*

<table>
<thead>
<tr>
<th>ISO 1268-7</th>
<th>Methods of producing test plates -- Part 7: Resin transfer moulding (RTM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AECMA prEN 6031</td>
<td>Determination of in-plane shear properties (+/- 45° tensile test)</td>
</tr>
<tr>
<td>AECMA prEN 6032</td>
<td>Determination of the glass transition temperatures, (Tg)</td>
</tr>
<tr>
<td>AECMA prEN 6033</td>
<td>Determination of interlaminar fracture toughness energy - Mode I Giic</td>
</tr>
<tr>
<td>AECMA prEN 6034</td>
<td>Determination of interlaminar fracture toughness energy - Mode II Giic</td>
</tr>
<tr>
<td>AECMA prEN 6035</td>
<td>Determination of notched and unnotched tensile strength</td>
</tr>
<tr>
<td>AECMA prEN 6036</td>
<td>Determination of notched, unnotched and filled hole compression strength</td>
</tr>
</tbody>
</table>
**Geometry verification**

Generally the geometric demands are more a result of the application than the material used, so most techniques used today for geometry measurements and verification should be easily transferred to composite applications. Nevertheless the following section contains some examples of testing methods and associated standards suitable for testing of geometry related issues.

<table>
<thead>
<tr>
<th>Property</th>
<th>Test method /Standard example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material thickness</td>
<td>ASTM E797-95</td>
</tr>
<tr>
<td>Dimensions and location</td>
<td>ISO 14253-1 to 3</td>
</tr>
<tr>
<td>Holes, roundness general</td>
<td>ISO 4291 and 4292:1985</td>
</tr>
</tbody>
</table>

The measurement of surface texture needs little explanation, it is important in several engine applications since air resistance is amongst other depending on surface roughness.

Material thickness might be measured using simple hand held tools if access to both surfaces is available. The method mentioned above is using Ultra Sonics and require access only to one side. Used correctly it should also be possible to gain knowledge about the shape of an enclosed cavity using this method.

The dimensions and location of product features are crucial to the function of the product. The suggested standards describes methods for linear distance measurements and roundness tests using, for example, Coordinate Measuring Machines (CMM).

### 4.3.2 Identification of thin areas

Generally, the supply of “back end operation”- standards, i.e. standards for the performing of product acceptance control regarding composite products is scarce. There are numerous standards in most standard systems describing ultrasonic testing, radiographic testing etc but mostly in a more general way. The most critical might be the lack of standards for NDE of fibre orientation, all methods for evaluating fibre alignment found during this investigation are destructive methods. Another interesting area is the quality testing of dry fibre preforms used for example for RTM. Especially if 3D weaved preforms are used they will have to be checked according to fibre orientation and pollution content before insertion in the mould. The quality of 3D reinforced preforms is to some extent monitored during manufacturing but some sort of quality assurance testing will be necessary in connection with final composite production as well. In appendix 2 some
assorted composite related standards recommended by DOT and FAA are listed.

5 CERTIFICATION OF COMPOSITE AEROSPACE PRODUCTS

In this section an investigation of what specific demands authorities makes to allow a composite aircraft structure to fly. [5, 6, 7, 8, 9, 10]

5.1 CERTIFYING AGENCIES, INTERNATIONAL AND DOMESTIC

Below some important certifying, or rulemaking, agencies for aerospace industry are presented shortly.

5.1.1 FAA

The Federal Aviation Administration is the national governmental agency for everything flight related in the USA. FAA states the rules and regulations for certification for everything from hang gliders to jumbo jets as well as personnel certification of pilots, mechanics and other support personnel.

5.1.2 EASA

EASA is, since a few years, the air traffic control organ in the European Union. EASA performs roughly the same tasks in the EU as the FAA in the Americas.

5.1.3 Luftfartsverket

The LFV is the Swedish governmental agency controlling air traffic in Sweden. LFV performs aircraft inspections and certifies pilots, other crewmembers, mechanics, traffic controllers etc. Since 2003 the EASA regulations have been accepted as the LFV rulebook as well as in all other EU countries.

5.1.4 Similarities and connections

As previously mentioned LFV and EASA have exactly the same regulations for air traffic and airplanes. But since the air transportation industry is so extremely international in its nature regulations does not differ much between EASA and FAA either. The similarities are there by necessity as
large differences would make international flights almost impossible or at least much more expensive.

5.2 COMPOSITE STRUCTURE CERTIFICATION

In this section specific regulations applicable on certificating newly developed composite aerospace structures is studied. On recommendations, from personnel at VAC, the focus is on the FAA regulations.

5.2.1 FAR, Federal Aviation Regulations

The FAR documents are the foundation for the FAA regulations. A search in the FAR regulations reveals little material specific for composites, at least not for structural applications. Some rules for design and manufacturing of wing details in composite material are available and might be applicable since it too has a “criticality of flight”-status, see FAR Sec. 23.573. Although composite specific rules are scarce some of the more general regulations will play a new and more determining role, for example the parts concerning statistically secured design values for material properties, fire protection and environmental effects on the material, i.e. environmentally imposed material degradation.

The FAR regulations are organized into 40 chapters, or parts, numbering from 1 to 193. The most interesting chapters for this thesis are:

- Part 21 – Certification Procedures for Products and Parts
- Part 23 – Airworthiness standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes
- Part 33 – Airworthiness Standards: Aircraft Engines

5.2.2 Circular Advisory documents

The FAA issues documents of recommendations, Circular Advisory, for suitable procedures for demonstrating compliance with the FAA regulations in chosen areas. The FAA points out that the methods described in these CA-documents are not the only way to show that a product is obeying FAA regulations; the methods described are suggestions.

There are a number of CA-documents concerning composite materials and they offer large amounts of useful tips for areas needed to be proven and/or checked both in the product development phase and in production. A number of CA-documents are listed under references. [7, 8, 9, 10]

5.2.3 Other documents

The FAA in cooperation with DOT, (Department Of Transportation), has issued a number of documents regarding suitable philosophy in FRP design which in content resembles the CA documents mentioned above. These also deliver usable tips for safe and reliable composite design. The perhaps most
extensive work published by the US government concerning composite materials is the MIL-17, (Military Handbook-17). The MIL-17 is not claimed to be a set of regulations but since many FAR and DOT documents uses the MIL-17 as a reference on proper composite design and manufacturing procedure it must be considered when deciding procedures to be used. The major lesson to be learned from the MIL-17, AC and DOT documents are proper determination of material properties through simple test panel manufacturing and testing. The AC and DOT documents also describes/lists necessary raw material and finished product tests needed to prove that the finished product is safe and ready to fly. [11, 12, 13, 17]

5.2.4 FAR regulations of interest for composite design

General
The impression when studying the FAR regulations is that the FAR Administrator responsible for issuing the approval for an engine, airplane or part is extremely powerful. The Administrator has the right to demand the execution of any test(s) that he sees fit. Especially in the case of, quote “a novel or unusual design feature of aircraft engine etc” the Administrator may prescribe special conditions that the product will have to meet.

In the area of “type design”, product drawings and specifications etc, the FAR demands that the documentation includes everything, drawings, material and process specifications etc needed to define dimensions and structural strength of the product. And of course that the detail tested to show compliance with the FAR regulations is manufactured and accepted in accordance to these drawings and specifications.

The manufacturer is acquired to establish and maintain a product control program that has to be approved by the FAA. The part manufacturer is mandated to prove that the quality control system established is capable to maintain a quality control that for every approved part guarantees that it fulfills the criteria in the type design. The control system includes, apart from the actual product testing, appropriate documentation on incoming raw material and parts bought from subcontractors. Further demands on the product control apparatus are:

- Incoming materials, and bought or subcontracted parts, must be properly identified if their physical or chemical properties cannot be readily and accurately determined. Furthermore material and bought parts will have to be inspected to show acceptable quality, the raw material for composites are to be tested on receipt from the supplier(s) on a batch to batch basis.
- Materials subject to damage and deterioration must be suitably stored and adequately protected.
- Processes affecting the quality and safety of the finished product must be accomplished in accordance with acceptable industry or United States specifications.
- Parts and components in process must be inspected for conformity with the type design data at points in production where accurate determinations can be made.
• Current design drawings must be readily available to manufacturing and inspection personnel, and used when necessary.

Additionally a review board consisting of materials and design specialists will have to be assigned to determine the eventual use of details which have quality issues but still are considered for use.

**Strength and deformation**
The structure must be able to support any load up to, and including, limit loads without suffering from permanent deformation or interference with the parts function. When experiencing ultimate loads the part must be able to support those for at least three seconds. Local permanent deformations are acceptable after ultimate loads if the part is considered spent afterwards.

Compliance to these regulations may be shown by analysis IF the structure is of typical and well known design for which analytical methods has proven to be reliable, otherwise tests are required. The values for Limit and Ultimate loads for engine mounts etc. shall be specified for the part in which the mounts are incorporated.

**Material general**
The FAR states some general requirements for the suitability and durability of materials intended for aerospace applications. The suitability must;

• Be established by experience or tests
• Meet approved specifications that ensure their having the strength and other properties assumed in the design data
• Take into account the effects of environmental conditions, such as temperature and humidity, expected in service

Furthermore it is stated that; “Workmanship must be of a high standard”. In addition material properties and design values must be based on enough tests of material meeting the specifications to establish design values on a statistical basis, (see for example ref [10]). When applying design values to the actual structure material strength values should be chosen depending on the criticality and design of the structure.

• Where applied loads are eventually distributed through a single member within an assembly, the failure of which would result in loss of structural integrity of the component; 99 percent probability with 95 percent confidence
• For redundant structure, in which the failure of individual elements would result in applied loads being safely distributed to other load carrying members; 90 percent probability with 95 percent confidence.

Although no specific remark to composite materials is made in FAR section 23.619, (and referenced sections). It is stated that if the material/structure strength is; uncertain, likely to deteriorate in service, or subject to appreciable variability due to uncertainties in manufacturing, a safety factor larger than the otherwise stated, and generally used, safety factor of 1,5 might be necessary to use.
Composite specific requirements

For airframe structures made of composite material there are special chapter(s) in the FAR, (section 23.573 for example). The regulations mention six points and two different approaches to show compliance to FAR by following all or some of the six points. The six points are:

1. It must be demonstrated by tests, or by analysis supported by tests, that the structure is capable of carrying ultimate load with damage up to the threshold of detectability considering the inspection procedures employed.

2. The growth rate or no-growth of damage that may occur from fatigue, corrosion, manufacturing flaws or impact damage, under repeated loads expected in service, must be established by tests or analysis supported by tests.

3. The structure must be shown by residual strength tests, or analysis supported by residual strength tests, to be able to withstand critical limit flight loads, considered as ultimate loads, with the extent of detectable damage consistent with the results of the damage tolerance evaluations.

4. The damage growth, between initial detectability and the value selected for residual strength demonstrations, factored to obtain inspection intervals, must allow development of an inspection program suitable for application by operation and maintenance personnel.

5. For any bonded joint, the failure of which would result in catastrophic loss of the airplane, the limit load capacity must be substantiated by one of the following methods:
   (i) The maximum disbonds of each bonded joint consistent with the capability to withstand the loads in paragraph (a)(3) of this section must be determined by analysis, tests, or both. Disbonds of each bonded joint greater than this must be prevented by design features; or
   (ii) Proof testing must be conducted on each production article that will apply the critical limit design load to each critical bonded joint; or
   (iii) Repeatable and reliable non-destructive inspection techniques must be established that ensure the strength of each joint.

6. Structural components for which the damage tolerance method is shown to be impractical must be shown by component fatigue tests, or analysis supported by tests, to be able to withstand the repeated loads of variable magnitude expected in service. Sufficient component, subcomponent, element, or coupon tests must be done to establish the fatigue scatter factor and the environmental effects. Damage up to the threshold of detectability and ultimate load residual strength capability must be considered in the demonstration.

As mentioned the part manufacturer is given the freedom to choose between two approaches to these demands. Either the manufacturer proves to comply with points one to four, (one to five when bonded joints exist), or else use points one, (five), and six which is most practical. In addition to these points
it is pointed out that the effects of material variability and environmental conditions on the strength and durability properties of the composite materials must be accounted for in the evaluations required. Inspection methods and procedures established and used in the above mentioned evaluations must be included in the Limitations section of the instructions for Continued Airworthiness, i.e. the rules for in service maintenance and inspections, which the user will have to follow.

Manufacturing
Generally the FAR states; if all pertinent process variables are adequately controlled, there is added assurance that the parts and structures produced will be acceptable. Quality control should, therefore, establish and implement a plan which verifies that: (1) the parameters affecting material integrity and process capability are operating under controlled conditions, and (2) individual items, batches, or lots conform to specified quality standards. To ensure that QC objectives have been met, process procedures should clearly define specific materials, tooling, equipment, cure cycle parameters, quality standards, operator qualifications, storage and handling requirements, traceability records, and any other special requirements. Of special interest for the composite development is the requirement that each new aircraft fabrication method must be substantiated by a test program.

Specifically on the production apparatus it is said that the methods of fabrication used must produce consistently sound structures. If a fabrication process, for example gluing, requires close control to reach this objective, the process must be performed under an approved process specification. Besides the actual process parameters the environment in the production facilities are to be closely monitored to assure low production variability. Examples of environmental aspects which need to be controlled are; temperature, dust, chemical substances and air humidity.

Lightning and fire protection
Generally every load carrying structure located in areas where there is risk for fire, the engine is naturally such an area, is mandated to have some degree of either; fire proofing incorporated in the structure, or fire protection in the form of heat shields or similar devices. The criticality of the structure and the relative proximity to the designated fire zones determine the degree of fire protection needed. No special remarks for the use of composites are made in the area of fire protection, but that fire protection is of special interest and creates special needs in the application of polymer composites is natural. It is though mentioned that the material used must minimize the probability of, and the spread of fire. During the material testing phase a comparison test between the composite material and aluminium is mandated for structures that are required to be fire resistant. The test pieces are to be subjected to a specified flame and the composite will need to withstand burn through as long, or longer, as the aluminium test piece.

In the area of lightning and lightning protection, the airplane and its structures is mandated to be protected from catastrophic effects from lightning. The protection should either minimize the effect of lightning on
the structure by some integrated design feature or else there will have to be added some appliance which diverts the lightning induced electrical current in a way so that the airplanes safety is not endangered. Since composite material may be considered as electrically conductive under certain circumstances consideration to this aspect is unavoidable.

**Containment, Ice and FOD**

In the field of containment of engine “debris”, broken rotor blades etc, the engine design is mandated to be able to contain all such debris. In the IMC case it may not be the actual containment demand that is the problem but more that it should remain intact after the broken off fan blade has passed the IMC.

The engine structures shall be protected against both ice build up and the hazard from ice sucked through the engine. In the case of potential ice build up some sort of deicing device is mandatory if it is necessary to avoid ice build up that can adversely affect the engine performance.

FOD, Foreign Object Damage, may be divided into three main areas, bird ingestion, hail ingestion and ice ingestion but also the ingestion of small particles as sand etc should be mentioned in this context. The bird ingestion tests, which are mandatory for engine certification, are divided into large bird ingestion and small and medium sized bird ingestion. The number of birds ingested into the engine in these tests depends on engine intake size, larger intake means more birds. For the large bird ingestion test a single bird whose weight depends on inlet size is ingested in the for the engine worst possible way regarding entry point and engine operation parameters. The pass limits for the large bird ingestion test includes little specific for the IMC but it will of course need to cope with loads resulting from the ingestion and survive the debris from the bird to fan impact. The small and medium size bird ingestion tests are intended to simulate an encounter with flocking birds. The amount, size and point of entry for the birds are specified depending on engine intake size. The engine is not allowed, as a result of the bird ingestion, to lose more than 25% of its maximum power and the engine will have to be able to continue to run for a specified time with no “unacceptable deterioration of engine handling characteristics”. These requirements might impose the need for some type of protection for the OGVs.

For ice ingestion the requirements specify that the engine shall manage to ingest an ice slab corresponding in size to the ice expected to accumulate on the engine inlet cowl during a two minute period without any deicing equipment activated. The engine must not sustain any permanent loss of power or need to be shut down after the ice ingestion.

Hail ingestion is much alike the bird ingestion tests in that sense that the amount and sizes of the hailstones ingested are depending on engine intake size. The speed of the ingested hailstones are however larger than in the bird test and the speed of the hailstones is one of the problems. There is for high entry speed a risk that a hailstone can enter the engine without ever hitting a
fan blade first. This makes for the IMC the need for being able to cope with harder impacts. The hail ingestion must not result in “unacceptable mechanical damage or unacceptable power or thrust loss after the ingestion, or require the engine to be shut down”.

Regarding sand and other smaller unwanted particles that may be sucked into the engine it is said that each structure needs to be suitable protected against weathering, corrosion and abrasion. Both the weathering and abrasion resistance demands will play a vital role regarding a composite IMC. This since the IMC is subjected to both water that may deteriorate the plastic matrix in the composite as well as small high velocity particles that may cause attrition damage upon the OGVs etc.

6 DISCUSSION AND RECOMMENDATIONS

Speaking in general terms there are both similarities and differences between making jet engine parts from metal compared to composite material.

The similarities are amongst others the general safety and quality thinking associated with the present manufacturing, tolerance setting etc. To continue on the subject of tolerances, regardless of the material, setting tolerances will always be a trade off between weight and cost, or differently put, price and performance. It is also important to consider the manufacturing process and production control apparatus capabilities when setting tolerances. If, in the future, composite manufacturing will be carried out at VAC the NDT equipment will have to be updated or exchanged since the equipment existing today is specialized towards metal. An example of this is made in appendix 1 where the ultrasonic equipment at VAC is tested on a flat laminate with more or less unknown properties. (The US-test was originally supposed to be succeeded by tests on the same laminate after subjecting it to a variety of impacts to determine the US abilities in damage detection, but my unfortunate accident which resulted in a broken leg made us, me and personnel at VAC, decide on the cancelling of those tests)

To relate to both the certification part and the standards part, NDT equipment chosen for the final production line will have to be evaluated and certified to assure that critical defects will be found in realistic geometries and standards for the inspection of realistic/real geometries will have to be developed.

In the field of governmental certification little specific on composite material is mentioned in the “rule book”. The conclusion is that the same basic safety and quality rules apply to composite material as well as metal, and both have to do the same job. The large “but” that I can see between the lines in the FAR legislation is that they have a very cautious approach to new technologies and the requirements keeps repeating that large amounts of testing will be needed before a material is approved in a new application. In addition to basic material data gathering extensive development and
testing of in service life inspection methods will have to be executed as well as the testing and deciding of fatigue life and service intervals.

When it comes to standards the first reflection I made was “doesn’t anyone make anything else than simple test panels/laminates?” Of the quite large array of standards regarding composites I would say that a large majority consider only simple flat unidirectional or multidirectionally reinforced test tabs used for basic material data gathering. Fortunately some of the standards for “test tab testing” might be useful for standardizing the testing of hang on bars. The most critical area, as I see it, lacking standards or perhaps even methods, are NDT/NDE of fibre orientation, in dry preforms as well as finished product, and general testing of material forming complex geometries.

As a natural continuation of the previous part my recommendations for continued work is to for example develop methods and standards for non destructive evaluating dry fibre preforms and fibre orientation in completed parts. But the array of options for further work is wide, most production parameters will have to be evaluated after material and production methods are chosen.
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Trollhättan 2005-02-03

Simon Nilsson
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[15] AECMA Online catalogue
http://www.aecma-stan.org/standards/standards.asp

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**APPENDIX 1**: Ultrasonic quick test at VAC

The test was performed using pulse echo method, 5MHz frequency and a 6” focused detector/receiver.

*Figure A1: Ultrasonic test rig*

*Figure A2: intensities of reflected signals*
The numbers in figure A2 refers to the signals in figure A1. The scale in the bottom of the graph shows distance in mm, if a correct number for the speed of sound in the composite is entered, (was not used here), the distance from 1 to 2 should be ~6mm i.e. the thickness of the composite. Normally when testing a more homogenous/continuous material, like steel or some other metal, the area monitored is that between points 1 and 2, and eventual changes in the material usually results in a clear and fairly easy signal to interpret. But as can be seen by the figure below, which is a magnification of that area from the figure above, it is very distorted and difficult to “make sense of” for the tested composite material.

![Graph of reflected signals](image)

*Figure A3: illustration of the complexity of the reflected signals*

However, trying to get something useful out of this test without having to fully understand the complex picture above, a graphical display of the amplitude of signal nr 3 was made. Simplified this picture is a chart of how “transparent” the material is for the signal in different areas.
Figure A4: Ultrasonic image of the tested material

The colour scale ranges from blue - least transparent, to red - most transparent. Unfortunately some colour information was lost when inserting it into this document. The biggest difference from the original is that the lighter blue areas are smaller here.

From this picture, A4, it can clearly be seen that there are areas different from the rest, but at this point nothing more can be said as no reference material with known properties was available at the testing occasion. (The clearly visible square area to the left of the picture is one of the supports seen in figure A1). A possibility would be to cut the material up and investigate for example the red areas to see what feature that resulted in the change in transparency at those points.

This test was performed primarily to quickly determine if the ultrasonic apparatus available at VAC was at all utilisable for composite testing. The answer is that it might be possible to use, but that more tests are necessary and the logical next step would be to run similar tests to this one on composite panels with defects of known type and size. As mentioned above, this test was performed using a frequency of 5MHz, and that is the lowest possible frequency which current transmitter/receiver handles. It would be interesting to perform tests using, down to or even lower than, 1MHz but then a new transmitter/receiver able to handle that frequency will have to be attained. With lower frequencies the resolution would decrease, as the size of the features possible to “see” is in the same order as the wavelength of the signal. A lower resolution might be an advantage though for detecting larger flaws in the material, this since the signal wouldn’t be so fuzzy from the echoes from small things like individual fibres etc.

A potential problem for the future is that the testing hardware requires more or less flat surfaces and in addition to that constant material thickness. Furthermore surface roughness affects the testing; the existing apparatus
prefers smooth surfaces. (The panel used for this test had a fairly rough surface). This might not be a problem for composites made by RTM, at least not for the outer surface but perhaps for hidden/interior surfaces? But for most prepreg lay up methods, (or other ply-stacking methods), a smooth surface is sometimes hard to get.

As seen in figure 8 in chapter 3.3 the potential of the U-S technique is high for flaw detection in composite material. Correctly used U-S equipment or a combination of several different U-S techniques gives medium to good chance of detecting most common flaw types such as for example delaminations, voids and impact damage.
APPENDIX 2:
Assorted standards recommended by DOT and FAA for composite testing.


ASTM C 393-00 Standard Test Method for Flexural Properties of Sandwich Constructions

ASTM C 613/C 613M-97 Standard Test Method for Constituent Content of Composite Prepreg by Soxhlet Extraction

ASTM D 792 Specific Gravity (Relative Density) and Density of Plastics by Displacement

ASTM D 2344 Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method

ASTM D 2471-99 Standard Test Method for Gel Time and Peak Exothermic Temperature of Reacting Thermosetting Resins

ASTM D 2734 Void Content of Reinforced Plastics

ASTM D 3039 Tensile Properties of Polymeric Matrix Composite Materials

ASTM D 3171-99 Standard Test Method for Constituent Content of Composite Materials


ASTM D 3530/D 3530M-97 Standard Test Method for Volatiles Content of Composite Material Prepreg


ASTM D 3878-01 Standard Terminology Composite Materials

ASTM D 4018-99 Standard Test Methods for Properties of Continuous Filament Carbon and Graphite Fiber Tows

ASTM D 4065-95 Standard Practice for Determining and Reporting Dynamic Mechanical Properties of Plastics


ASTM D 3479-96 Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials


ASTM D 5379 Shear Properties of Composite Materials by V-Notched Beam Method

ASTM D 5418 Standard Test Method for Transition Temperatures of Polymers by Differential Scanning Calorimetry


ASTM D 5687-95 Standard Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation

ASTM D 5766-95 Standard Test Method for Open Hole Tensile Strength of Polymer Matrix Composite Laminates

ASTM D 5961-01 Standard Test Method for Bearing Response of Polymer Matrix Composite Laminates


ASTM D 6484-99e1 Standard Test Method for Open-Hole Compressive Strength of Polymer Matrix Composite Laminates
ASTM D 6641-01e1 Standard Test Method for Determining the Compressive Properties of Polymer Matrix Composite Laminates Using a Combined Loading Compression (CLC) Test Fixture

ASTM D 6742-01 Standard Practice for Filled-Hole Tension and Compression Testing of Polymer Matrix Composite Laminates

ASTM D 5528-01 Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites

ASTM D 6115-97 Standard Test Method for Mode I Fatigue Delamination Growth Onset of Unidirectional Fiber-Reinforced Polymer Matrix Composites

ASTM D 6415-99e1 Standard Test Method for Measuring the Curved Beam Strength of a Fiber-Reinforced Polymer-Matrix Composite


ASTM D 6507-00 Standard Practice for Fiber Reinforcement Orientation Codes for Composite Materials

ASTM E 168 General Techniques of Infrared Quantitative Analysis

ASTM E 1252-98 Practice for General Techniques for Obtaining Infrared Spectra for Qualitative Analysis

ASTM E 1309-00 Standard Guide for Identification of Fiber-Reinforced Polymer-Matrix Composite Materials in Databases


ASTM E 1434-00 Standard Guide for Recording Mechanical Test Data of Fiber-Reinforced Composite Materials in Databases


ASTM E 1640-99 Standard Test Method for Assignment of the Glass Transition Temperature by Dynamic Mechanical Analysis

ASTM E 2041-99 Method of Estimating Kinetic Parameters by Differential Scanning Calorimetry Using Borchardt and Daniels Method

ASTM E 2070-00 Test Method for Kinetic Parameters by Differential Scanning Calorimetry Using Isothermal Methods
ASTM E 4473-95 Standard Practice for Measuring the Cure Behavior of Thermosetting Resins Using Dynamic Mechanical Procedures

SACMA SRM 1R-94 Compressive Properties of Oriented Fiber-Resin Composites

SACMA SRM 18R-94 Glass Transition Temperature (Tg) Determination by DMA of Oriented Fiber-Resin Composites

SACMA SRM 20R-4R High-Performance Liquid Chromatography of Thermoset resins

SACMA SRM 22R-94 Resin Flow of Preimpregnated “B” Staged Material

SACMA SRM 23R-94 Resin Content and Fiber Areal Weight of Thermoset Prepreg with Destructive Technique

SACMA SRM 25R-94 Onset Temperature and Peak Temperature for Composite System Resins Using Differential Scanning Calorimetry (DSC)