# Structural Resin Transfer Moulding - Design, Manufacture & Simulation

by

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## Abstract

The weight savings available from the use of composites can often be offset by the high material cost and autoclave manufacturing costs. Resin Transfer Moulding (RTM) has the potential for cost competitive high performance composite fabrication. This closed mould process offers a single stage moulding of complex components employing new preform technologies and resin systems, reducing part count, increasing repeatability and aesthetics, while providing health and safety improvements over traditional fabrication methods. Computer based design tools will reduce the development time and cost required in the introduction of a new production component. This will be of particular use to the low volume, diverse product range industries where high development costs are difficult to amortise. As with any new manufacturing technique, the quality of the resultant components must be monitored according to the process parameters, and control procedures standardised. This paper describes the work ongoing in two collaborative projects. The first is concerned with the design of a process simulation, and a knowledge based system. The second looks at how various quality control methods can be related to the quality assurance of RTM manufactured components.

## 1. Introduction

Resin Transfer Moulding (RTM) is not a new technology. It has been around for many years and has found a definite market in many high volume, low and intermediate performance manufacturing industries, not least among these the automotive industry. The advantages of the RTM process in the composite industry are well documented - near net moulding, reduced part count, one shot production, reduced storage of refrigerated materials, removed the need to use expensive autoclave procedures, reduced wastage and more environmentally friendly. However it is only within the last five years that the aerospace industry has begun to take advantage of this process. The advent of structural RTM resins systems and various preform technologies have opened the door to a cost competitive, high performance fabrication route.

Significant weight savings are available from the use of advanced composites but this is often offset by high material and autoclave manufacturing costs. In some cases composite parts have been over designed again negating many of the potential savings. The RTM process provides us with a clean slate from which we can design the parts and optimise the manufacturing process to take advantage of all that composite materials can offer us.

However, the development of any new part via a new manufacturing process is costly. The development of a proven manufacturing route for a production component may require much proto-typing work. The RTM process may produce one of the following defects : (i) the resin may start to gel before the component is completely filled or (ii) the resin flow may cause air entrapment producing voidage within the part. To overcome this the location of vent ports and the process conditions have to be selected to ensure complete wetting out and wetting through of the part, and, we must have a comprehensive working knowledge of the materials with which we are dealing.

Previously the selection of the process parameters has been a matter of trial and error, combined with experience. Examination of a range of all the available options, and the various modifications required to do so, is expensive and becomes difficult to amortise in lower production rate industries. This in turn may cause a reluctance to take up the technology despite the advantages available in the long run, unless suitable design tools are available. The question of monitoring and assuring part quality is also an important question when dealing with a a variety of new materials and process conditions.

## 2. Design Tools

Within the BRITE EURAM sponsored ' Simulation of the Resin Transfer Moulding Process for Efficient Design and Manufacture of Composite Components'-SIMRTM project, two computer design tools are being developed:

(i) a process simulation and
(ii) a knowledge based system.

They are aimed at predicting events during the moulding cycle and at making recommendations on the material selection, and the process conditions that are required to fill the mould. They will also produce advise on the effect of the process variables and the material selections made, and on the mechanical properties, which are of particular importance in the design of aerospace structures.

One of the major tasks associated with the development of these two design tools for the RTM process is the acquisition of repeatable, reliable and accurate data. Currently the properties of materials used in the RTM process are poorly defined and this limits the effectiveness of the simulation techniques. A wide range of data characterising the resin system and the fibre reinforcement is required. The resin system characterisation includes viscosity time/temperature relationships, reaction kinetics data, energies of reaction and thermal characterisation for different states of cure, to be performed by the Swedish Institute of Composites. The fibre characterisation includes permeability and thermal characterisation, material drape and conformability for different geometry's. In addition, data must be complied on the final composite performance, in particular the mechanical performance, and how this can be related to quality assurance methods employed in the inspection of the part.

### 2.1.1 Permeability Measurement

The reinforcement permeability is perhaps the most critical characteristic from a process simulation point of view. The aim of the work is to produce a database of permeability's for different reinforcements and correlate these with lay-up configurations and the fabric microstructure.

To measure this quantity, two different techniques are being developed at separate research centres. These techniques have been tested on a base-line material, Unifilo U750-450 glass fabric. This was chosen because it is widely used within the composite industry. Later this work will concentrate on the higher volume fraction carbon reinforcements. TNO P&RRI in Delft have designed and manufactured an adjustable mould tool for the measurement of the permeability, as shown in Figure 1, where the resin flow is investigated using pressure transducers. This considers one-dimensional resin flow to determine the permeability values. Initial results have shown a very good repeatability, within 5%.

The University of Plymouth have produced a fixed mould tool, where the advance of the resin front is monitored via a video camera. This rig employs a central injection gate and measures the permeability in two directions. The results produced by both institutions will be correlated to establish consistency or non-consistency. If the latter is the case the causes of the differences will be determined. This work will be extended to investigate lay-ups including several fabric types to verify that the Rule of Mixtures can be used for combinations of reinforcements. This work also includes the effects of pore spacing and forming processes on permeability.

### 2.1.2 Mechanical Performance of the Final Composite

The injectability of the resin and its ability to wet out the fibres affects the final resin/ fibre interfacial bond, and therefore the mechanical performance of the component. It is important to understand how these processing conditions affect the mechanical performance from the component design viewpoint. Brochier SA are determining the effect of the process conditions on the interlaminar strength, flexural strength/modulus, compressive strength and glass transition temperature for two resin systems and two fabrics. The resin systems are Ciba LY564-1 and RTM6 and the fabrics are Brochier 283g/m$^2$ 5 harness satin weave fabric and an Injectex version of the same fabric. Examination of the design properties, tensile strength, open-hole compression and open-hole tension are being performed by the Royal Institute of Technology, Stockholm for both resin systems with the standard 5 harness fabric.

## 2.2 Process Simulation

A primary aim of the SIMRTM project is to produce a process simulation which will model complex three-dimensional components. The process simulation being developed follows two tracks. The first builds upon existing simulation expertise for the injection moulding process. Two pieces of software are being used, SEPRAN [1] and VIp [2]. To make the simulation specific to RTM the following software additions are being written:-

(i) software to represent the reinforcement permeability for resin flow through a porous media.
(ii) software to represent the mixture of composite materials of varying volume fractions.
(iii) software to take account of the reaction kinetics of the resin.
(iv) software to predict the heat generated during cure.
(v) software to take account of the composition of the composite.

The latter three modules will be used to predict the heat transfer during the injection portion of the cycle and the likelihood of the resin starting to cure during the injection phase of the cycle, together with the cure kinetics and peak exotherms occurring in the resin and the thermal balance in the mould. The simulation is being developed in blocks which are validated through comparisons with actual moulding work. This will be discussed later. A schematic of the design methodology is shown in Figure 2. The first code developed considered the injection phase of the process, for two-dimensional panels. Development of the simulation at TNO P&RRI has now completed the three-dimensional model. It allows the modelling of various features including cores, inserts, variable section, differing flow path lengths over the surface of the component, as well as local curvature.

The next stage in the development of the simulation is the incorporation of heat transfer solutions. This will enable temperatures, and therefore viscosity variations that occur during the injection process, to be included in the simulation. This will improve the accuracy of the filling phase as well as allowing the cure portion of the process to be modelled fully. The problem currently being addressed, and one of the critical issues in the implementation of the heat transfer modules, is the coupling of the flow and heat equations, where the flow fronts of the resin either converge or diverge.

The desirability of a simplified PC based version, targeted specifically at RTM, has been identified, and will form the second track of the simulation development. It will be developed independently of the SEPRAN and VIp software, but utilising the expertise gathered during the work station development outlined above.

1. SEPRAN is a fluids finite element library.
2. VIp is produced by the Einhoven University of Technology, The Netherlands. VIp is used to solve three-dimensional heat transfer equations and two-dimensional pressure distributions within a three-dimensional geometry.

To make the PC version self contained, the development of the software will commence with the writing of modules for input and output and a mesh generator. The final versions of both the PC, and VIp workstation based software, will be two independent programs able to model the flow of a non-Newtonian and reacting resin through a medium of variable permeability in a three dimensional moulding.

## 2.3 Knowledge Based System

To produce a set of a design rules for the RTM process an Intelligent Knowledge Based System (IKBS) is being developed, incorporating the information gathered during the programme and the 'expertise' already accumulated by the consortium partners in the RTM field and in composites in general. The proposed system accepts as inputs behavioural requirements and provides a design specification as a solution to the design problem. This design specification has the form of a set of parameter values which may be subsequently used as input for the RTM process simulation model.

The IKBS development is based around five modules, as shown in Figure 3. The first of these deals with the material selection for RTM based upon their properties. The system will advise on the material choices available for a given application, and the effect of that choice on all relevant properties. The initial data on which the decision will be made will include fabric permeability, resin viscosity, the pore space /permeability relationships, edge effects and mechanical performance. The rules for this module are nearing completion, but the database of properties has to be completed.

The second module builds on this incorporating the results from the two-dimensional moulding work. This will include design rules for resin flow and cure in two-dimensional components. The IKBS will incorporate the effect of processing variables, mould and component configuration, to predict the processing conditions required to ensure complete component fill while achieving a high quality component. The processing options being considered include gating configuration, material choice, mould temperature, injection pressure and vacuum pressure applied.

This will then be extended to include the data from simple, intermediate and complex three-dimensional mouldings progressively. It is intended that the IKBS will include design rules which deal with the incorporation of cores and inserts, curvature and stiffening features. The rules for each component of increasing complexity considered, will built upon those of the previous stage. The rules are being derived by INASCO Hellas, in consultation with the other project partners, and programmed by INTRACOM SA. The system is being developed using a work station based expert system - but the usefulness of a PC mounted system has been identified as critical. Therefore the rule base structure being derived is being translated into KAPPA PC, an PC oriented expert system.

## 2.4 Mould Tool Optimisation

Currently the design of an RTM tool is based upon combined experience of the customer requiring the tool and the toolmaker. Often the lack of experience on both parts results in costly mistakes and lack of optimisation. Sonaca SA is producing a systematic review of the tooling options selected by the partners in designing their specific components, and a literature review of existing methodologies within the RTM fraternity. The intention is to create a design guide for RTM tools, to determine and quantify the issues facing the resin transfer moulder and designer, to ensure that the mould design is optimised. The following options will be examined : mould material. mould inertia, port configuration, heating, clamping, part removal and mould conditioning. A summary of this work will ultimately be included in the IKBS.

## 2.5 Validation

To direct and validate both of the design tools outlined above, a moulding programme of increasing complexity has been included within the SIMRTM project. In the early stages of the project the moulding work is being used to identify critical process factors, direct and validate the simulation work, and as a data source for the IKBS process design modules. The programme will mirror the development of the design tools evolving to include the features to be found in each component type. These features and the partner responsible for them, are summarised in Table 1. In the later stages of the project the programme will be geared to validating the predictions *made by* the design tools.

Initial validation work has been carried out by TNO P&RRI comparing simulation predictions with the mouldings manufactured using Unifilo U750-450 reinforcement - see Figure 4. These results indicate that once the initial phases of the injection cycle have been completed the accuracy of the results are quite good. The initial discrepancies in the results have been attributed to the pressure losses that occur due to the pipe work and injection equipment. Once the injection reaches a steady state the effects of the equipment are less pronounced. It is expected that with the higher fibre volume fraction mouldings the effect of the equipment will be further reduced and can be discounted.

Some preliminary work has also been performed by British Aerospace Airbus Limited, for input to the first IKBS process module, using the Inasmet moulding data. It is important to be able to predict the time it will take the mould to fill. By comparison of this with the gel time of the resin system being considered, it can be estimated whether or not the mould will fill. A suitable time interval must exist between the time to fill and the time to gel, to permit fibre wet out. The mould fill time is dependant on many varying and interdependent factors, including the fibre volume fraction, the permeability of the reinforcement, the viscosity of the resin, the mould pressure difference, and of course the critical length (the maximum flow path length).

We shall express this simply as :

$$t_{fill} = k\,L^2 \qquad (1)$$

where $t_{fill}$ = fill time, k = fill constant, L = critical length.

The Inasmet moulding work produced plots of the advance of the resin for centrally injected glass and polyester panels. Other types of gating may require the fitting of other forms of equations. Using this data, a regression analysis was performed using BBN/Experimental Software, which uses a least squares method of regression. This enables the determination of the k in the equation above. This is only valid for specific processing conditions, and set-up, **exactly the same** as those used in a particular moulding by Inasmet.

The BBN/Experiment software was then used to determine the effect of the processing variables on k. As we discussed earlier, the fill constant k, is dependant several factors. A design of experiments approach was used to determine the importance of the fibre volume fraction, the tool temperature, and the injection pressure, and derive a linear equation for k.

## 3. Quality Assurance

To improve the likelihood of the RTM process being introduced into the production environment it is essential to develop process control measures to ensure that the composite material produced will give acceptable structural properties and repeatability. As part of the lead in to a project sponsored by the Department of Trade and Industry entitled the 'Quality Assurance of Composite Details by Resin Transfer Moulding'- QUARTM, this problem has been addressed. The 'lead-in' programme is the first step in investigating the RTM process using a Design of Experiment approach to determine which variables affect the quality, as inferred from Non Destructive Testing (NDT) techniques and the mechanical performance of the composite material.

### 3.1 Materials

The materials investigated in this work were three RTM resins A, B, C in conjunction with a standard 283g/m$^2$ 5 harness satin weave using aerospace T300 grade carbon fibres. Resins A and B are mono-component systems and of a higher specification that the two part resin C. The features of these resin systems are summarised in Table 2. The panels were manufactured using peripheral injection, with vacuum assist applied at the centre of the panel. The resin A panels exhibited the fastest fill times. The thicker panel in the B and C resins exhibited the same fill times, while the thinner panels filled twice as quickly with the B resin system.

### 3.2 Non Destructive Evaluation

The non destructive evaluation work was carried out using a Meccasonics ultrasonic c-scan, by the Defence Research Agency. A nominal frequency of 5MHz was used and a 6mm collimator added to reduce the beam width to improve the resolution. Each scan was gated in 0.5dB steps. One panel of each resin type was scanned to assess the range and distribution of attenuation levels in the material. All of the panels attenuated at different levels, enabling a distinction to be made between the different resin systems. It also proved possible to identify differences in quality across a panel, to detect damage areas, and determine whether it is a surface effect or through-the-thickness damage.

Resin C was the most attenuative material with a range of 24-30dB. Resins A and B attenuated at similar levels with ranges 21-25dB and 21-27.5dB respectively - see Figure 5, each colour represents a particular attenuation level, the darker areas equating to the better quality areas of the panel. Some variation across the panel is notable. The panel made from resin A attenuated most consistently.

Each panel was then scanned individually, within its own range. This showed more definitely that the panels made from resin A exhibited the most consistent quality across the panel, while those made from resin B and C appeared to be of better quality around the centre of the panel and poorer towards the corners. This could be due to the following. The resin, preheated to slightly below the mould temperature, is injected at the periphery. Therefore as the resin travels towards the centre of the mould the resin temperature rises and the viscosity drops, which may lead to better fibre wet-out in the central region. Alternatively the central vacuum point may exert a stronger vacuum at the centre which led to better wet-out. As the resin A panels were of consistent quality it seems that resin A is more easily processed, the viscosity being thought to be sufficiently low at entry into the tool.

All the c-scans revealed a central problem area. Further investigation showed this, in some cases, to be a through-the-thickness effect rather than just a surface effect. This area coincided with the resin sprue at the vacuum point. The damage may have been caused when the resin sprue was detached from the panel after it had gelled. Where damage was identified, the size of the damage area was found to be about 10mm in diameter. The c-scans also revealed a difference in attenuation, and therefore quality, between panels manufactured with the same resin system, under the same processing conditions. The most marked appearance of this occurred with resin C, the two component system. These anomalies warrant further investigation and may have significant implications for the repeatability of RTM processing. Defects that show up on the ultrasonic scans may be due to a variety of things, ranging from porosity and voids to an increase in local thickness or surface effects. Microsectioning is an efficient way of determining the source of such a scan defect. In a resin B panel, a microsection showed that a number of voids corresponded to an area of increased attenuation of the ultrasonic scan - see Figure 6.

### 3.3 Glass Transition Temperature and Moisture Uptake

The glass transition temperature measurements were performed by British Aerospace Airbus Limited, using a TA Instruments 983 Dynamic Mechanical Analyser according to specification AITM 1.0003. The room temperature specimens were dried out at 70°C. The hot/wet test specimens were conditioned at 70°C, 95% relative humidity for 1000 hours. Three specimens were tested at each condition.

The results are given in Table 3. They show that in the dry condition resins A and B perform significantly better than resin C. Resin A performed the best. The hot/wet conditioned test results show resin A exhibited the largest drop in Tg, while resin B exhibited the smallest drop. However, resin A's Tg is still higher than that of resins B and C. Table 3 also shows the moisture uptake for the three resin system composite panels. Resin A shows the greatest uptake while resin B exhibits the least. The QUARTM project will investigate if the low moisture uptake, actually translates to better mechanical performance for the systems under consideration .

### 3.4 Mechanical Testing

In order to access the effect of the process parameters on the mechanical performance of the panels, a selection of mechanical tests were completed : short beam interlaminar shear strength (ILSS), flexural strength and modulus, compression before and after impact. The glass transition temperature was also measured in dry and hot/wet conditions.

#### 3.4.1 ILSS and Flexural Testing

The ILSS and flexure specimens were tested at room temperature after drying at 70°C, according to test procedures defined in pr_EN 2563, by British Aerospace Airbus Limited. Five specimens were tested at each condition. The results showed distinct differences between the three resin systems. Resin B performed the best, then resin A and finally resin C. However when the standard deviations are taken into account, there was little to distinguish between resin B and resin A, see Table 4. Microstructural examination of the failed specimens revealed that none of them had a visible failure mode in line with pr_EN 2563. This will be further investigated in the DTI project.

The flexural modulus test results showed no significant difference between the resin systems, all giving values around 60 GPa. Microstructural examination confirmed all specimens failed in the manner expected according to the test specification. The flexural strengths showed clear differences between the resin systems. Resin A performed best with resin B and then resin C, see Table 4.

### 3.4.2 Compression After Impact

The procedure followed is that set out in ACOTEG ACO/TP/10. Two specimens 152.4mm x 101.6mm were cut from each 4.6 mm thick panel, either side of the central sprue area. The specimens were impacted with a 3kg falling weight, tup diameter 15.7mm, in a Boeing support fixture aperture 125mm x 77mm. The impact energy was controlled by varying the drop height. Restrike was prevented by catching the weight after the first impact. One specimen of each material type was impacted with increasing energy to determine the energy required to cause threshold damage, defined as 20mm across. The damage was accessed by ultrasonic scanning of the specimens between impacts. Three specimens were then impacted at 1.2 x the threshold energy value determined, and two more at 2x the threshold energy. The threshold energy was taken to be that which caused the damage size nearest to the prescribed 20mm across, in joules. Resin C displayed the lowest threshold value while resins A and B exhibited similar results - see Table 5. The damage areas corresponding to the 1.2x and 2x threshold energy impacts are also reported in Table 5. The ultrasonic scans showed that visible damage does not always correlate with the damage reflected by the C-scan. Generally resin A displayed a slightly greater damage area than resins B and C.

The compression testing was carried out on a Schenk 400kN servohydraulic test machine. The specimens were supported in an antibuckling test rig according to Boeing specification BS7260, and loaded to failure at a constant crosshead speed of 1 mm/min. Three strain gauges were bonded onto the specimens, two on one side and one on the other, to check alignment and flag if buckling occurred prior to failure. The results, before and after impact, are also shown in Table 5. Before impact resin B displayed the highest compressive strength, followed closely by resin A and lagged significantly by resin C. This order is maintained for both the 1.2x and 2x threshold impact specimens although the different between resin C and the other two resins has narrowed considerably. This would seem to correlate with the fact that in general the percentage reduction in compressive strength due to the impact event, is less for the resin C panel. At the 1.2x threshold impact energy resin A and resin B showed a reduction in compressive strength of 30% and 32%, while resin C showed only an 18% reduction. At the 2x threshold impact energy the reductions of resins A, B and C are 41%, 40% and 30% respectively. It should be noted here that the NDE scan of resin C panel, showed poor quality, and the low undamaged compressive strength may not have been typical. This would in turn affect the percentage reduction values.

Failure of resin A and resin C specimens occurred close to the end. There is no significant difference between the failure strains of resins A and B, but that of resin C is 25% lower, see Table 5. The resin A specimen was the only one that began to buckle prior to failure (at approximately 90% failure load). The percentage reductions in strain follow the same trend as that of the compression strength. Generally it can be concluded that resin A and B panels are more resistant to impact, with resin B being the superior of the two, since it exhibits a lower damage area for the same threshold value, and higher residual strength values. This work was carried out by the Defence Research Agency.

## 4.0 Reinforcement Architecture in RTM

Within the main QUARTM project a second reinforcement, a non crimp fabric, will be considered, as well as the 5 harness satin weave. Non crimp fabrics are only one of a wide range of preform architecture's and techniques that are now available to the RTM designer. These architecture's include, warp and weft knitting, 3D weaving, interlock, triaxial weaving, 2D braids, 3D braids, 2.5D fabrics, uniweaves, and of course stitching. Many of these architecture's include through the thickness reinforcement. This provides the potential for enhanced delamination and impact resistance, without other mechanical property penalty's, which has historically been a drawback in the use of advanced composites. The developing weaving and textile industries are capable of generating complicated preforms that could not easily be laminated via the traditional autoclave route. Such preforms enable one shot mouldings of complex parts, via the RTM process. These new technologies combined with the new generation of RTM resins, some of which have been discussed in section three, have increased the attainable fibre volume fraction in RTM to rival that of prepreg methods.

## 5.0 Conclusion

The development of the design tools, material characterisation, and established quality control methods will increase the probability of the introduction of the RTM process and the variety of advantages it offers to the composite industry. It has been shown how a materials characterisation, simulation and a knowledge based system can be inter-related to produce a comprehensive design methodology. The value of certain mechanical testing, ultrasonic testing, and microsectioning has been proven in monitoring the quality of RTM produced components. However, while this project will provide the computer tools for process design and development, and the required material characterisation techniques, it will be necessary to widen the database of materials considered. The techniques demonstrated in this work form only a starting point. To improve the take up of the technology it will be necessary to produce standards, for the acquisition of material properties, and quality control methods. This, plus a recognised need for portability of the computer systems being developed, onto other platforms, will mean that the end users of these tools and methods can be extended to those outside the constituent project partners.

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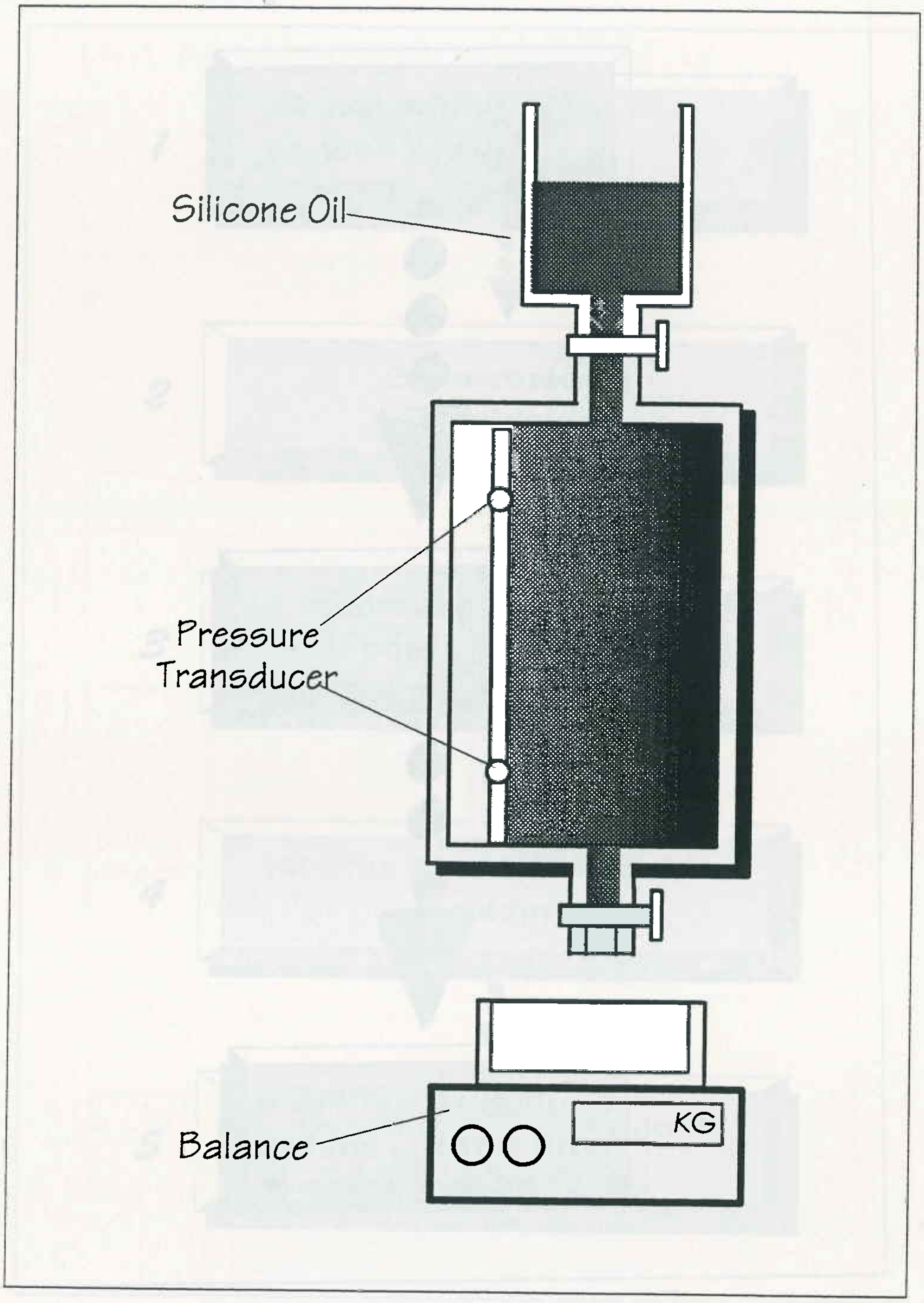


Figure 1 : TNO P&RRI Permeameter Design

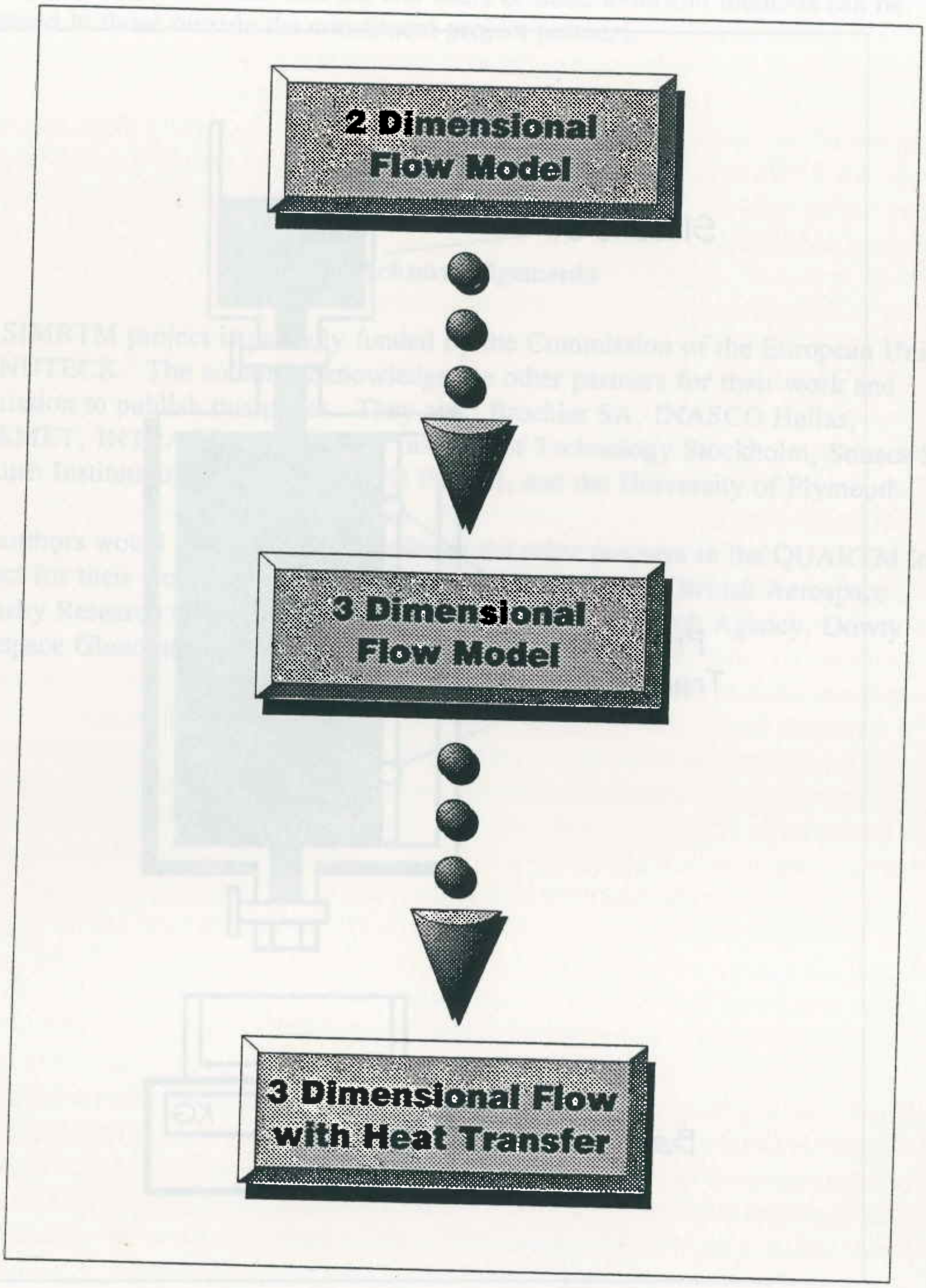


Figure 2 : Stages in Simulation Development

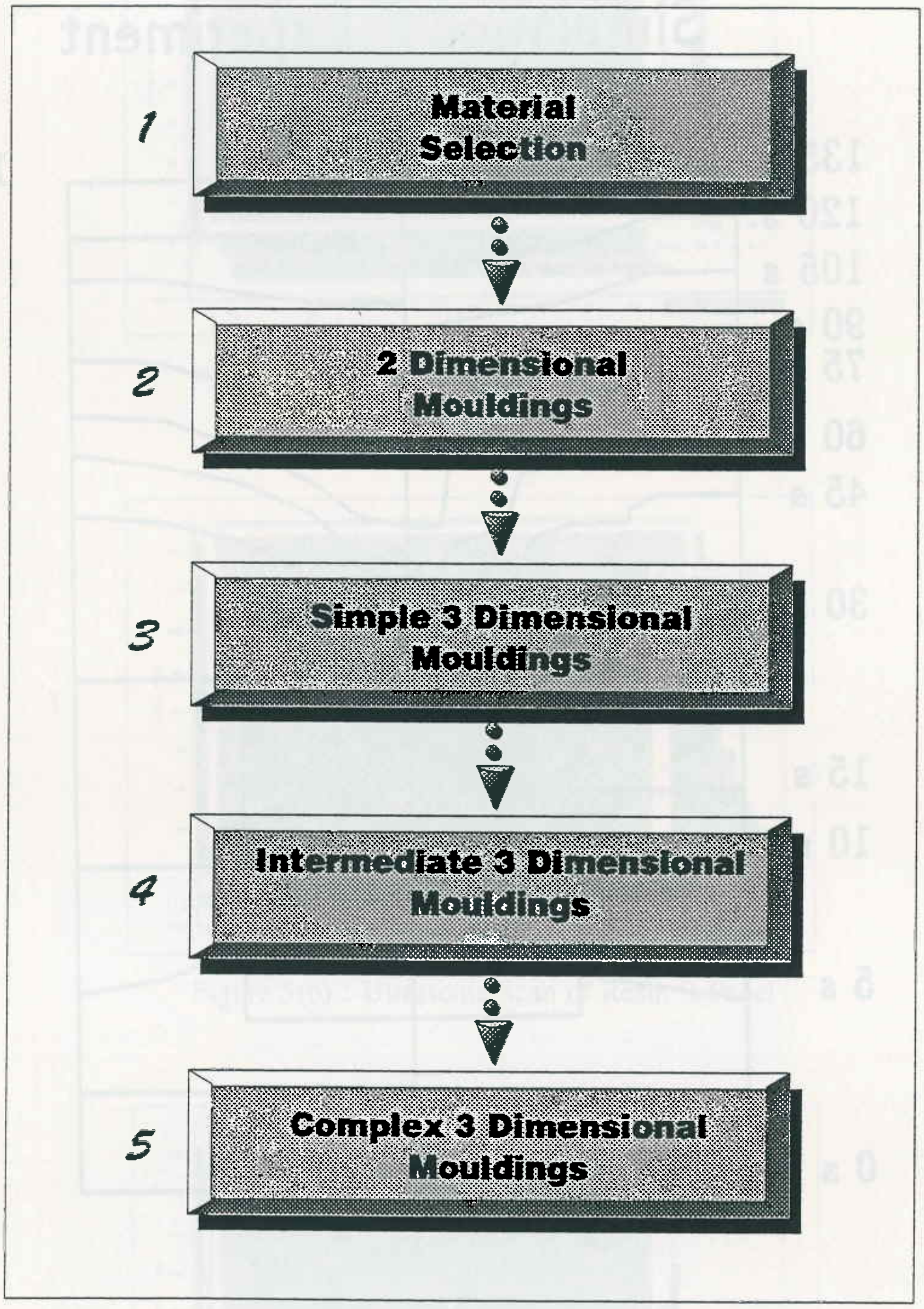


Figure 3 : Modular Structure of IKBS

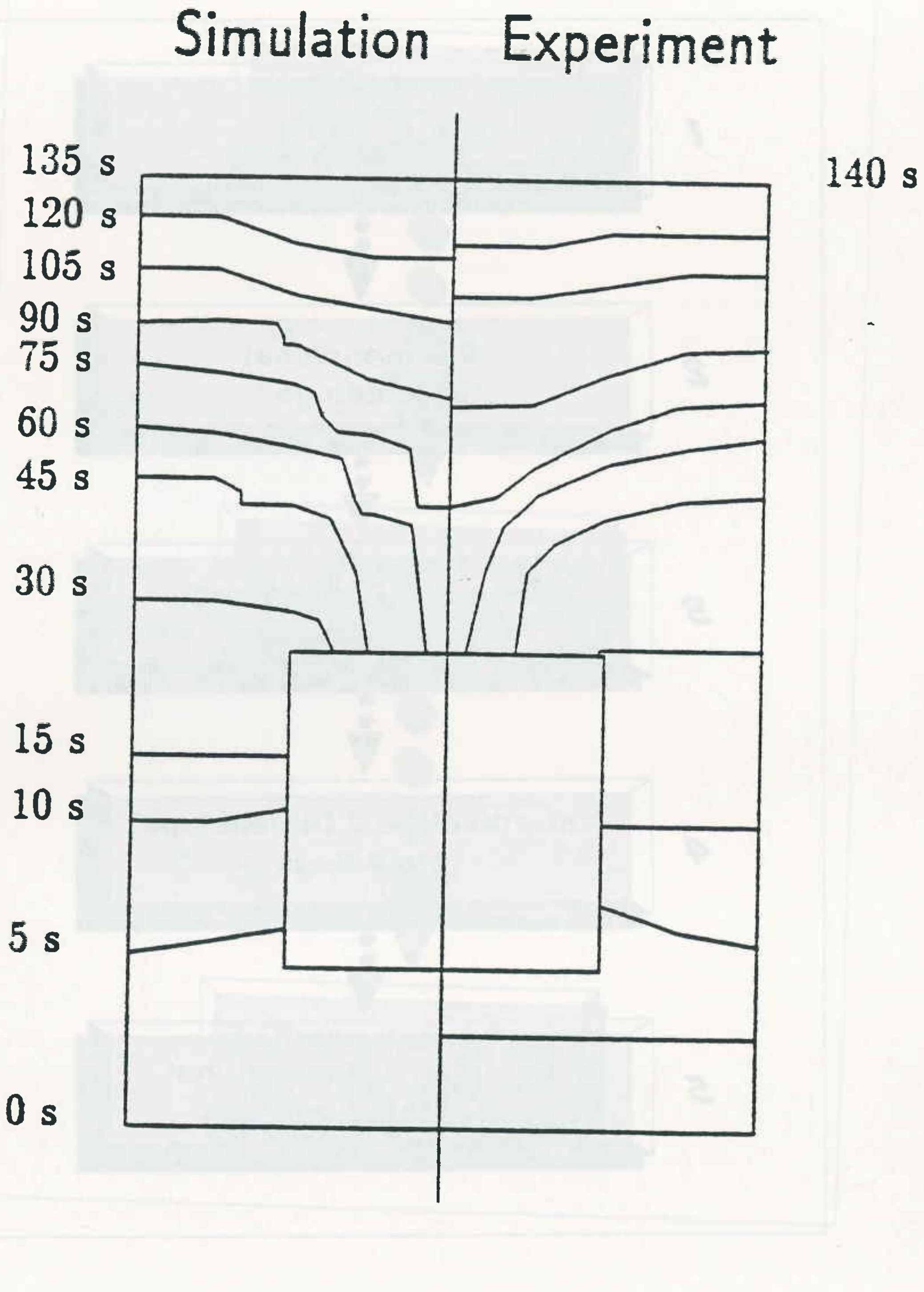


Figure 4 : Comparison of Moulding and Simulation Results

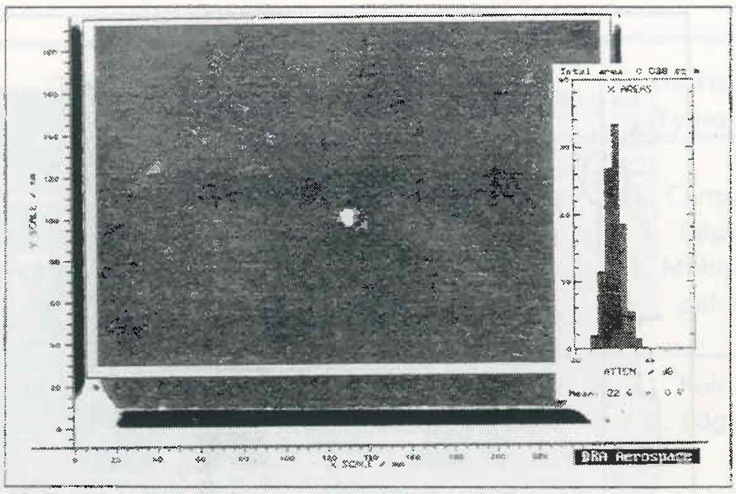


Figure 5(a) : Ultrasonic Scan of Resin A Panel

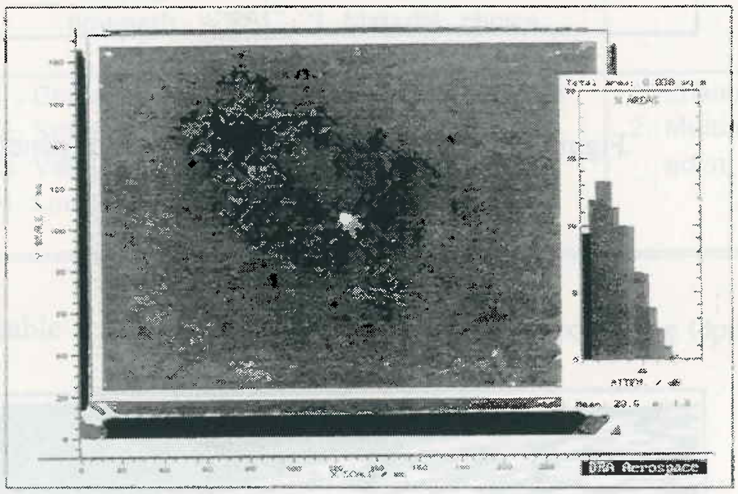


Figure 5(b) : Ultrasonic Scan of Resin B Panel

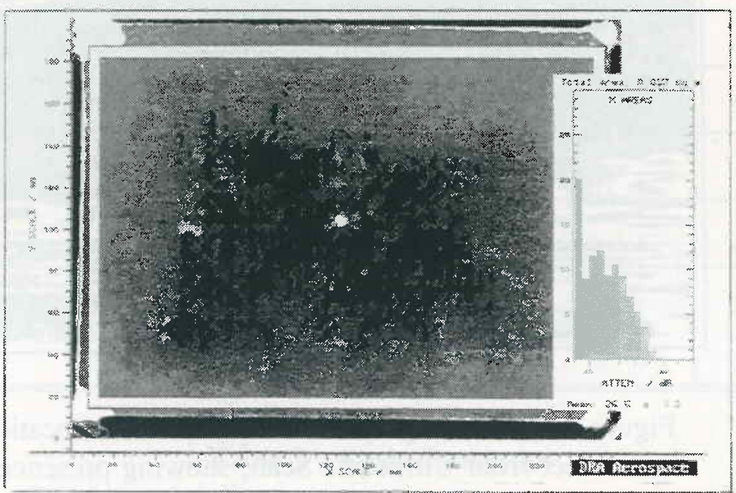


Figure 5(c) : Ultrasonic Scan of Resin C Panel

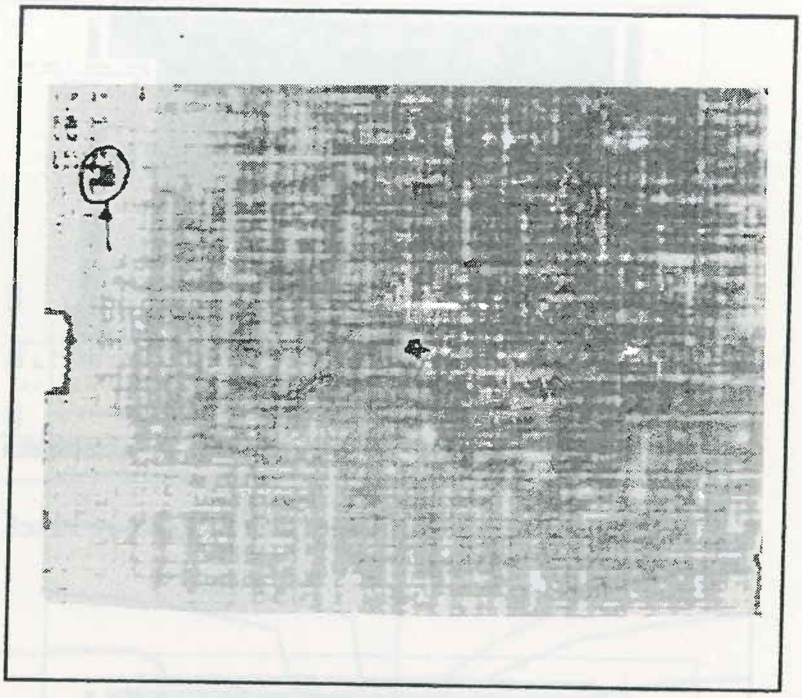

Figure 6(a) : Ultrasonic Scan of a resin B panel showing location of defect

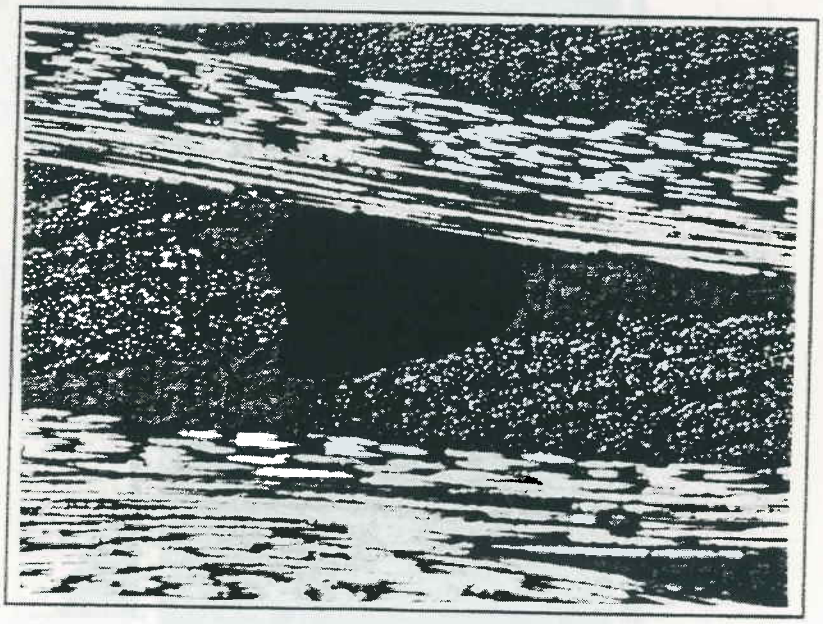

Figure 6(b) : Micrograph of resin B panel at location of defect from Ultrasonic Scan, showing presence of voids

| Component Complexity | Component Configurations | Process Options | Gating Types | Responsible Partners |
|---|---|---|---|---|
| 2-Dimensional | 1. Component thickness<br>2. Volume fraction | 1. Tool temperature<br>2. Injection/Vacuum pressure<br>3. Material choice | 1. Central<br>2. Edge<br>3. Multiple point | Brochier SA<br>INASMET<br>University of Plymouth |
| Simple 3-Dimensional | 1. Cores/inserts<br>2. Varying flowpath | 1. Tool temperature<br>2. Injection/Vacuum pressure<br>3. Material choice | 1. Point<br>2. Edge | INASMET<br>Brochier SA |
| Intermediate 3-Dimensional | 1. Curvature<br>2. Stiffeners<br>3. Varying flowpath | 1. Tool temperature<br>2. Injection/Vacuum pressure<br>3. Material choice | 1. Multiple point<br>2. Edge | Short Brothers<br>Sonaca SA |
| Complex 3-Dimensional | 1. Cores/inserts<br>2. Stiffening features<br>3. Varying flowpath<br>4. Local curvature | 1. Tool temperature<br>2. Injection/Vacuum pressure<br>3. Material choice | 1. Channel<br>2. Multiple point | British Aerospace Airbus Ltd. |

Table 1 : Component Configurations and Processing Options

| Resin System | Resin A | Resin B | Resin C |
|---|---|---|---|
| Market | High Performance | High Performance | Medium Performance |
| Toughened | Semi | Yes | No |
| Type of System | One Part | One Part | Two Part |
| Tool Temperature(°C) | 120 | 160 | 70 |
| Viscosity at Tool Temperature (Poise) | 0.7 | 0.35 | 1.5 |

Table 2 : Resin Properties

| Resin | Dry Tg (°C) | Wet Tg (°C) | Moisture Uptake (%) |
|---|---|---|---|
| Resin A | 222 (1.2) | 182 (1.0) | 1.139 |
| Resin B | 203 (0.9) | 176 (0.1) | 0.718 |
| Resin C | 152 (1.7) | 129 (1.5) | 0.975 |

Table 3 : Glass Transistion Temperature and Moisture Uptake
(standard deviations in brackets)

| Test | Lay-up | Thickness | Resin A | Resin B | Resin C |
|---|---|---|---|---|---|
| SBS ILLSS (MPa) | (0/90,0/90,0/90,0/90,<br>90/0,90/0,90/0,90/0) | 2 | 62.5(1.7) | 70.1(3.5) | 53.1(1.5) |
| Flexural Modulus (GPa) | " | 2 | 60.2(0.7) | 59.9(0.5) | 60.5(0.9) |
| Flexural Strength (MPa) | " | 2 | 1073(28.4) | 1045(51.5) | 945(72.3) |

Table 4 : ILSS, Flexural Test Results
(standard deviations in brackets)

| Test | Lay-up | Thickness | Resin A | Resin B | Resin C |
|---|---|---|---|---|---|
| Undamaged Compressive Strength (MPa) | (+45,0/90, +45,0/90, | 4.5 | 385 | 391 | 296 |
| Undamaged Failure Strain ( μ ) | +45,0/90, +45,0/90)s | 4.5 | -10124(986) | -9574(385) | -7250(821) |
| Threshold Energy (Joules) | (+45,0/90, +45,0/90, | 4.5 | 9 | 9 | 7 |
| | +45,0/90, +45,0/90)s | | | | |
| 1.2x Threshold Energy (Joules) | " | 4.5 | 10.8 | 10.8 | 8.4 |
| Longitundinal Damage (mm) | " | 4.5 | 19 | 18 | 18 |
| Transverse Damage (mm) | " | 4.5 | 22 | 22 | 22 |
| Visible Damage | " | 4.5 | Back spilt | Back spilt | None |
| | | | Front dent & split | Front dent | |
| Damaged Compressive Strength (MPa) | " | 4.5 | 261(10) | 273(6) | 242(8) |
| Damaged Failure Strain ( μ ) | " | 4.5 | -5760(309) | -6542(288) | -5960(204) |
| 2x Threshold Energy (Joules) | " | 4.5 | 18 | 18 | 14 |
| Longitundinal Damage (mm) | " | 4.5 | 27 | 25 | 23 |
| Transverse Damage (mm) | " | 4.5 | 28 | 25 | 26 |
| Visible Damage | " | 4.5 | Back spilt | Back spilt | Back split |
| | | | Front dent & split | Front dent & split | |
| Damaged Compressive Strength (MPa) | " | | 226(8) | 241(5) | 211(6) |
| Damaged Failure Strain ( μ ) | " | | -5507(777) | -5721(400) | -5056(88) |

Table 5 : Compression/Impact Properties
(standard deviations in brackets)