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# Consolidation of thick, close, circular knitted glass fiber textiles with epoxy resin into flat panels, tubes and T-profiles

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## Abstract

*A method was developed to produce composites of fiber reinforcements with thermos matrices. The method consists mainly of two steps: impregnation and consolidation. A dry reinforcement is bagged in a vacuum bag and fiber wet-out occurs by Resin Transfe Impregnation, drawing the resin through the reinforcement by applying vacuum. The impregnated laminate is then consolidated in either an autoclave or a press.*

*Molds for flat panels, T-profiles and tubes were designed and built for the autoclav application.*

*Circular knitted glass fiber tubes (E-glass) and epoxy resin (Bisphenol F) wer processed in these molds employing the developed impregnation/consolidation method.*

*Flat panels, consolidated under different conditions, were tested for their physical, chemical and mechanical properties. Fiber volumes of more than 60% were attained. Th measured void volumes were all below 0.5%. A tensile strength of 170 MPa wa determined for laminates of four layers which were cured at 250°F (121°C) for 8 hrs und 50 psi and 100 psi (3.4 bar and 6.8 bar) respectively. Curing at 350°F (176°C) led to micro cracks in the laminate which impaired the mechanical properties.*


## 1 Introduction

Of the various different textile structures which have been used as reinforcement in fiber reinforced plastics, little use has been made of knitted structures since good mechanical properties were not expected. Recently, it was shown that strength and stiffness properties of composites made from knitted structures are similar to those made from some woven fabrics.[1] Specific advantages of using knitted reinforcement structures are low production costs, and high flexibility and drape. Good fabric drape allows the fabric to lay down onto complex shapes. Additionally, since knitted fabrics have good elongation and elasticity they can be stretched easily over molds to produce 3D-shapes. The mechanical properties have even been shown to improve when the reinforcement is stretched.[1] Thus, knitted structures may be a good alternative to common reinforcements such as 3D-weaves or -braides.

One of the major problems that arises with reinforced plastics is voids entrapped in the parts during impregnation. Voids impair the mechanical properties of the product. The thicker and the denser the reinforcement is, the more difficult it is to achieve proper, void free impregnation.

This paper describes an impregnation method that provides low void content in the laminate. Knitted glass fiber textiles were impregnated using this method and different parts were produced such as: flat panels, tubes and T-profiles. Physical, chemical and mechanical properties of the flat panels were tested for fiber and void volume, strength and stiffness, etc.

## 2 Materials

### 2.1 Reinforcement - Knitted Glass Fiber Tubes

E-glass (25.4 g/cm$^3$) 158B-AA-675 Type 30 from Owens-Corning Fiberglas Corporation/Ohio was used as reinforcement.[2] These fibers are specially developed to provide quick wet-out and low fuzz. They are treated with silane for epoxy compatibility. The yarn of 735 tex (675 yd/lb) contains 2000 endless glass filaments (k-type = 13.6 µm diameter).

The yarn was circular, weft knitted into tubes with a plain single jersey knit structure (courses/wales: 10/8 in$^{-1}$ (4/3.2 cm$^{-1}$)). The knitted glass fiber tubes had a nominal diameter of 3.2'' (81.3 mm) and an average fabric area weight of 36.6 oz/yd$^2$ (1240 g/m$^2$).

As a lay flat tubing of 5" (127 mm) width before consolidation, the fabric was pressed to a flat panel which then had a width of 5 1/8" (130.2 mm). The fabric area weight then decreased to 34.8 oz/yd$^2$ (1180 g/m$^2$) in the cured part.

### 2.2 Matrix - Epoxy Resin

#### 2.2.1 Resin

The reinforcement was combined with an epoxy resin in a wet process. The resin used was an epoxy Bisphenol F (BPF) called EPON Resin DPL-862 manufactured by Shell Chemical Company. It is a low viscosity liquid epoxy resin manufactured from Epichlorohydrin and Bisphenol F. This resin is specially developed for filament winding and resin transfer molding.[3]

#### 2.2.2 Curing Agent

The curing agent used with EPON Resin DPL-862 was EPON Curing Agent W (formerly Research Curing Agent RSC-763) consisting of an aromatic amine. The mixing ratio (resin : curing agent) used was 100 : 26.4 (w/w).

#### 2.2.3 Accelerator

EPON Curing Agent Accelerator 537 was recommended for catalyzation of the cross linking process. However, it was not used since the impregnation of the reinforcement required resin with a long gel time.

### 2.3 Cured Laminates

Parts of three different shapes were produced: flat panels, T-profiles and tubes (fig. 2.1). The manufacturing procedures are described below.

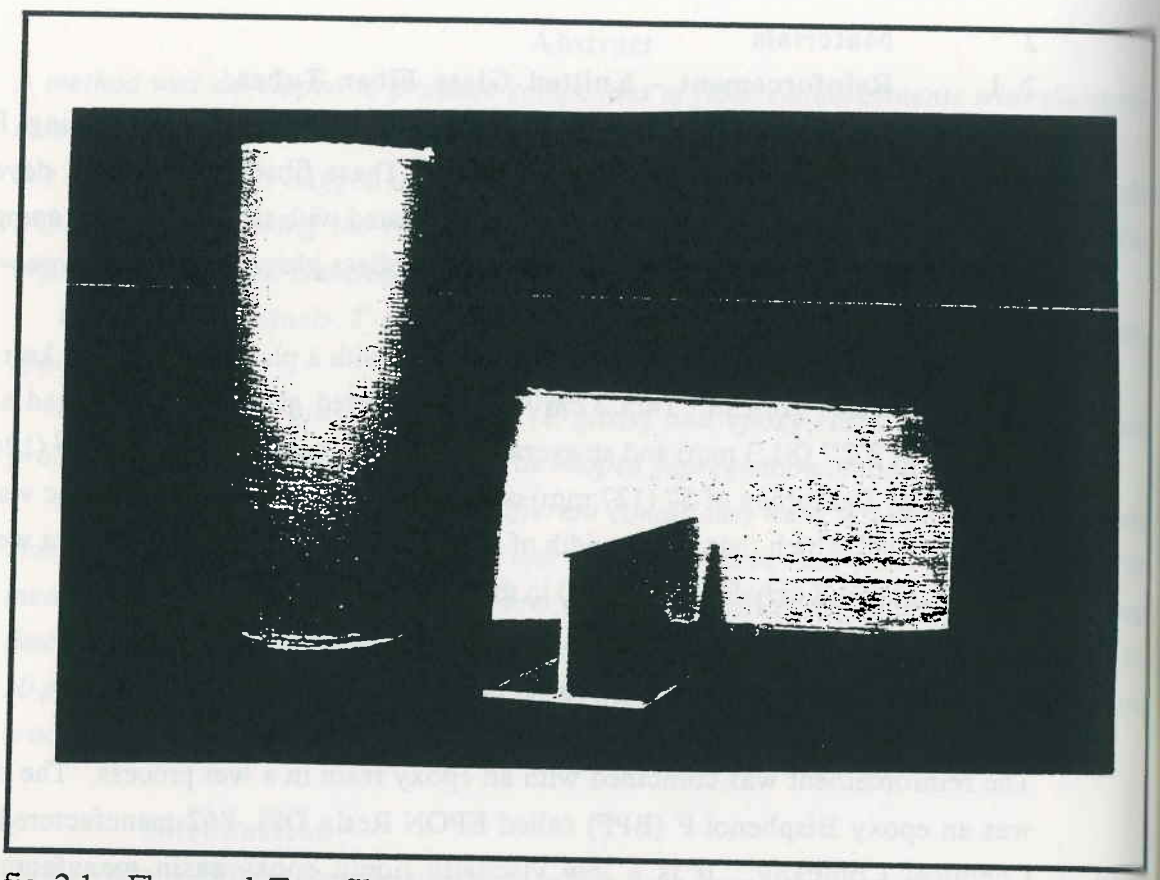


fig. 2.1: Flat panel, T-profile and tube

## 3 Processing Method

A processing method was implemented which was suitable for all three shapes and which also provided good control of fiber-to-resin ratio and low void volumes. Therefore, a combination of both, autoclaving and resin transfer molding (RTM), was developed combining advantages of both processes into a single process. This processing method generally comprises as a first step the impregnation of a dry reinforcement with RTM, providing:

a) a clean process,

b) a process with no air entrapment;

and as a second step the consolidation of the impregnated reinforcement in an autoclave, providing:

a) cheap tooling of complex shapes,

b) fiber volume control by adjusting the autoclave pressure,

c) high fiber volume.

## 3.1 Equipment

Consolidation was accomplished in an autoclave (a press is suitable for parts of simple shape such as flat panels). Nitrogen was used as an inert atmosphere. Computer control provided ramps and soaks for both gas pressure and gas temperature. Two vacuum lines fed into the autoclave. Each line was connected to a separate vacuum pump. The vacuum pumps were both manually adjustable.

## 3.2 Molds

In the developed processing system, the reinforcement was placed between molds generating two smooth surfaces on the cured laminate. The molds were part of the lay-up and, therefore, they were designed to provide round edges so that they would not damage the bagging film .

Flat panels were simply placed between two plates (see fig. 3.5).

The mold for the T-shaped composites consisted of three parts: two angle beams and a bottom plate with a lower center to keep the reinforcement from sliding sideways (fig. 3.1).

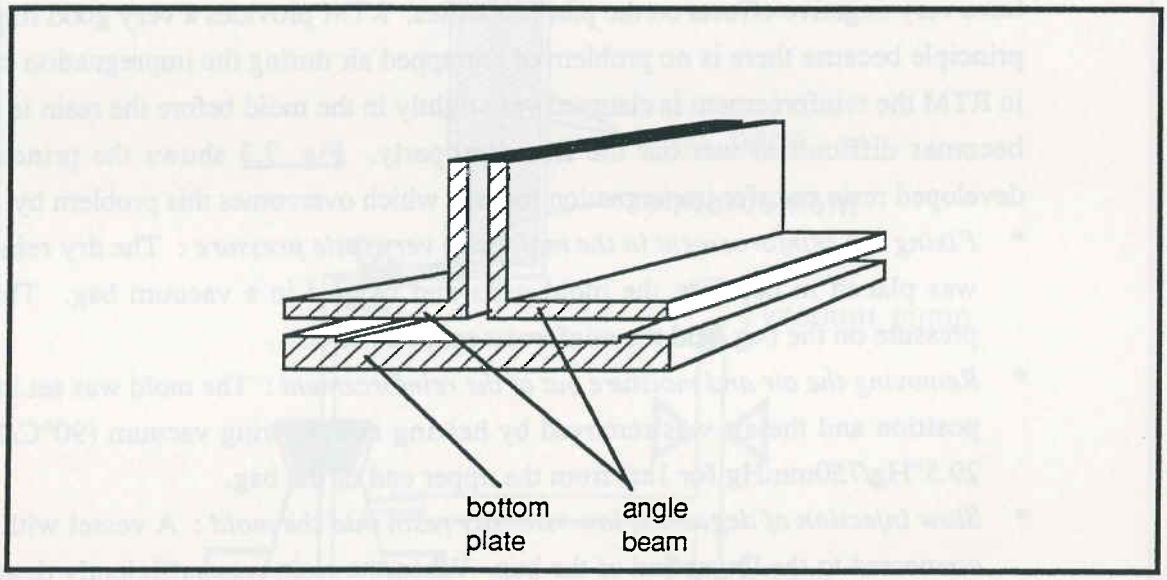



fig. 3.1: Mold for T-profile

The mold for the tube consisted of a cylindrical aluminum tube over which the reinforcement was pushed. Thus, the autoclave heat was transferred to the lay-up from both the inside and the outside of the tube. To obtain a smooth outer surface, a sheath of thin metal with an axial slit was placed around the reinforcement. The axial slit closed during consolidation (fig. 3.2).

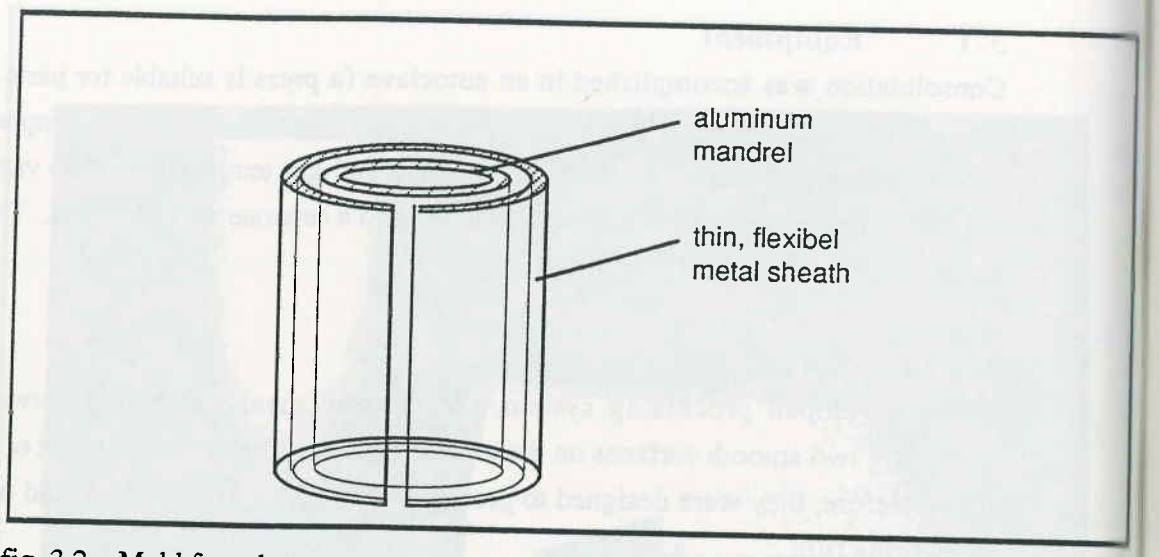



fig. 3.2: Mold for tube

## 3.3 Resin Transfer Impregnation

Impregnation is a very critical step since poor fiber wet-out, voids, and entrapped air can have very negative effects on the part properties. RTM provides a very good impregnation principle because there is no problem of entrapped air during the impregnation step. Since in RTM the reinforcement is clamped very tightly in the mold before the resin is injected, it becomes difficult to wet out the fibers properly. Fig. 3.3 shows the principle of the developed resin transfer impregnation method which overcomes this problem by:

* *Fixing the reinforcement in the mold with very little pressure* : The dry reinforcement was placed in between the mold parts and bagged in a vacuum bag. The ambient pressure on the bag held the reinforcement in position.
* *Removing the air and moisture out of the reinforcement* : The mold was set in a vertical position and the air was removed by heating and drawing vacuum (90°C/176°F and 29.5"Hg/750mmHg for 1hr) from the upper end of the bag.
* *Slow injection of degassed, low viscosity resin into the mold* : A vessel with resin was connected to the lower end of the bag. When the resin was sufficiently degassed (80-90°C and 29.5"Hg vacuum for 15 min), the connecting line was opened. The vacuum applied to the resin reservoir was released slowly in order to create a resin flow (1" to 2"/min) through the reinforcement to the top end of the bag into a resin trap.

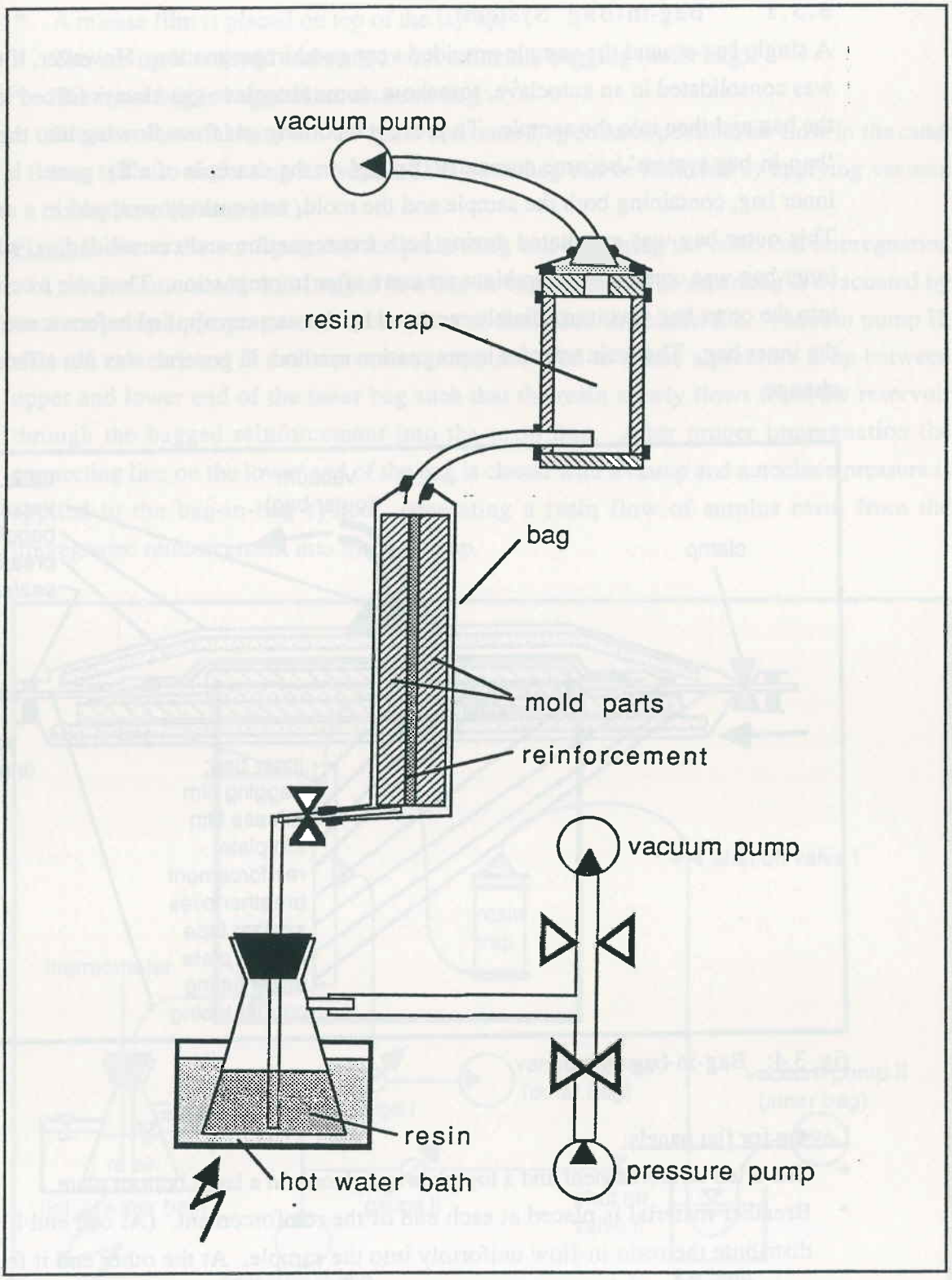



fig. 3.3: Resin transfer impregnation method

### 3.3.1 'Bag-in-Bag System'

A single bag around the sample provided very good impregnation. However, if the sample was consolidated in an autoclave, somehow, some autoclave gas always forced its way into the bag and then into the sample. To prevent incoming gas from flowing into the sample, a 'bag-in-bag system' became necessary (fig. 3.4 on the example of a flat panel) in which the inner bag, containing both the sample and the mold, was entirely wrapped in a second bag. This outer bag was evacuated during both impregnation and consolidation, whereas the inner bag was connected to ambient pressure after impregnation. Thus, air forcing its way into the outer bag was immediately removed by the vacuum applied before it could get into the inner bag. The resin transfer impregnation method, in general, was not affected by this change.

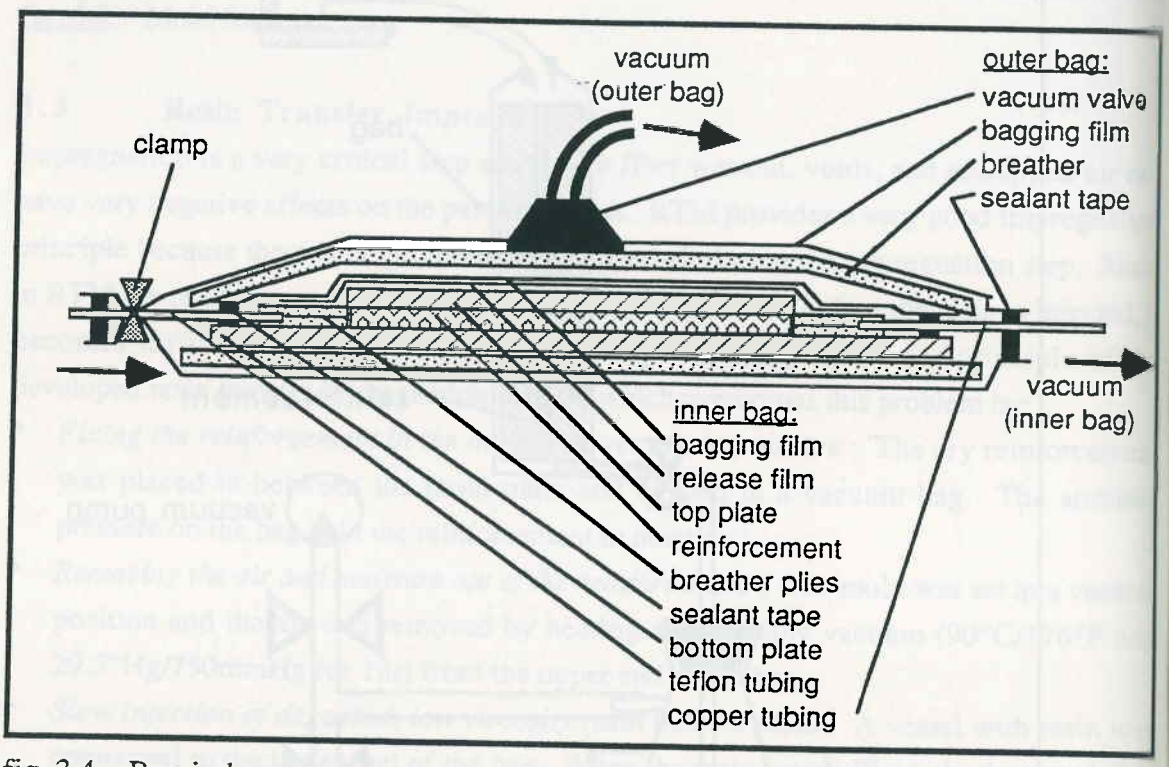



fig. 3.4: Bag-in-bag system

Lay-up for flat panels:

* The dried reinforcement and a top plate are placed on a large bottom plate.
* Breather material is placed at each end of the reinforcement. (At one end it serves to distribute the resin in-flow uniformly into the sample. At the other end it focuses the resin flow toward the resin outlet.)
* Teflon tubing leads from the resin reservoir to the breather material.
* Copper tubing is attached between the breather plies and connected to a resin trap.

* A release film is placed on top of the lay-up.
* The lay-up is covered and sealed with a flexible bagging (inner bag).
* The inner bag is bagged into an outer bag.
* Breather material between the inner and outer bag ensures possible air flow in the outer bag. (Thus, air forcing its way into the outer bag can be removed by applying vacuum to the breather material.)

Fig. 3.5 shows the configuration for preheating and degassing the resin and impregnation of a reinforcement which is bagged in a bag-in-bag system. The outer bag is evacuated by vacuum pump I. Impregnation takes place as described in section 3.2. Vacuum pump II, shut off valves I and II and a pressure pump are used to create a pressure drop between upper and lower end of the inner bag such that the resin slowly flows from the reservoir through the bagged reinforcement into the resin trap. After proper impregnation the connecting line on the lower end of the bag is closed with a clamp and autoclave pressure is applied to the bag-in-bag system, generating a resin flow of surplus resin from the impregnated reinforcement into the resin trap.

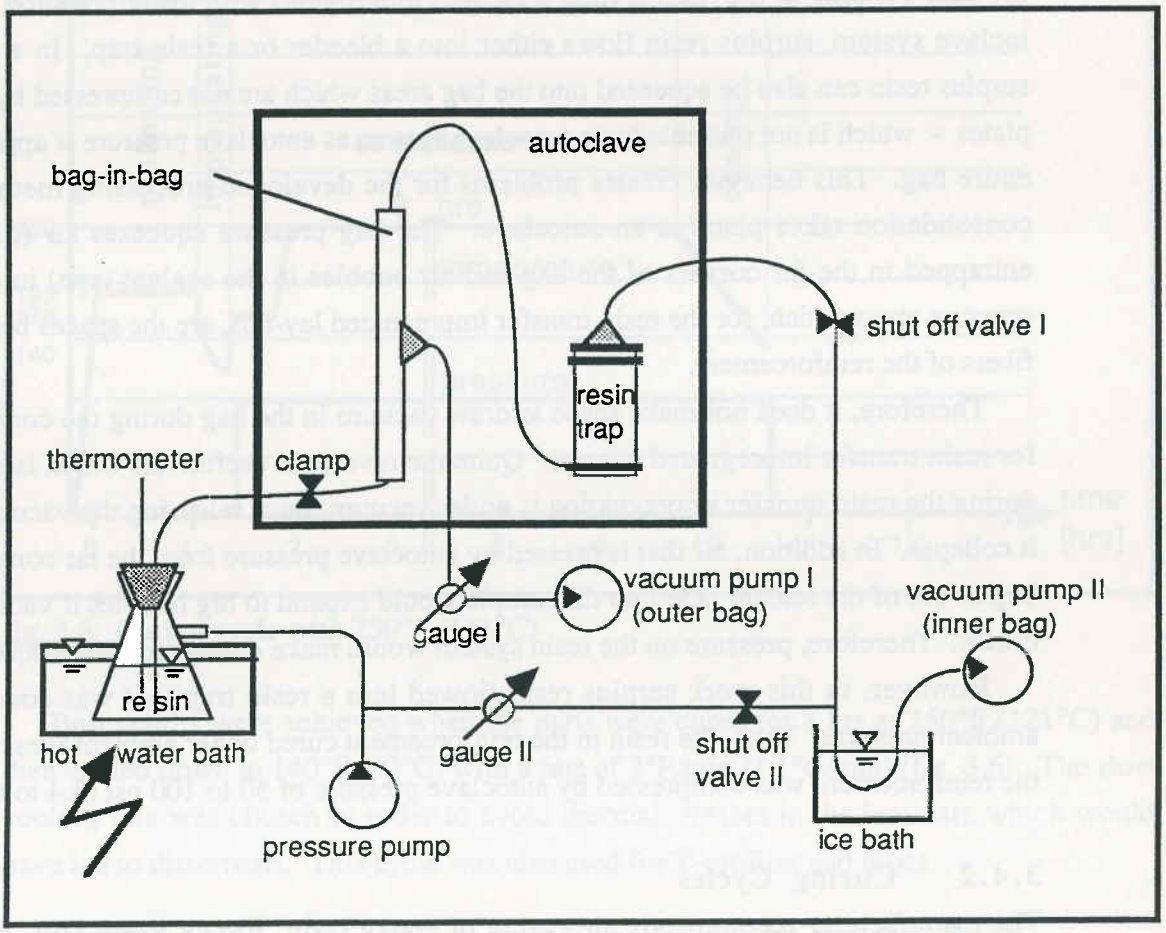



fig. 3.5: Configuration for preheating, degassing and impregnation

## 3.4 Consolidation

The reinforcement was consolidated in an autoclave (optionally in a press) combining the application of pressure and heat. Pressure was applied in order to:

* generate a bleed out of surplus resin,
* densify the laminate,
* force the resin into the bundles of fibers.

Heat was applied in order to:

* decrease the viscosity of the resin during the first 20 min of consolidation,
* accelerate the cross linking process of the polymers in the resin.

### 3.4.1 Theoretical Background

The following discussion addresses the possible effects of the pressure on the sample during the beginning of the consolidation, while the resin still has low viscosity.

A sample which is bagged and impregnated as described in section 3.3 can be consolidated either in a press or in an autoclave. Both systems apply pressure on the outside of the bag. As long as the resin is fluid it escapes into regions with lower pressure. In an autoclave system, surplus resin flows either into a bleeder or a resin trap. In a press, the surplus resin can also be squeezed into the bag areas which are not compressed by the mold plates - which is not possible in an autoclave system as autoclave pressure is applied to the entire bag. This behavior creates problems for the developed processing method when consolidation takes place in an autoclave: The bag pressure squeezes air (such as air entrapped in the far corners of the bag and air bubbles in the sealant tape) into the low pressure areas which, for the resin transfer impregnated lay-ups, are the spaces between the fibers of the reinforcement.

Therefore, it does not make sense to draw vacuum in the bag during the consolidation for resin transfer impregnated lay-ups. Quite the reverse is useful: air which is entrapped during the resin transfer impregnation is under vacuum, thus, releasing the vacuum makes it collapse. In addition, air that is pressed by autoclave pressure from the far corners of the bag or out of the sealant tape into the sample would expand to big bubbles if vacuum were drawn. Therefore, pressure on the resin system would make entrapped air collapse.

However, in this work surplus resin flowed into a resin trap that was connected to ambient pressure. Thus, the resin in the reinforcement cured under ambient pressure while the reinforcement was compressed by autoclave pressure of 50 to 100 psi (3.4 to 6.8 bar).

### 3.4.2 Curing Cycles

The manufacturer recommends the curing of epoxy resin 'EPON Resin DPL-862' with 'EPON Curing Agent W' for 2 hrs at 350°F (177°C) or for 8 hrs at 250°F (121°C).[3] Flat

panels were produced with both cycles. Some flat panels were subjected to 0 psi autoclave pressure, others to 50 psi and 100 psi.

In the first part of all cycles the entire lay-up was preheated in the autoclave to the impregnation temperature of 195°F (90°C) for 1 hr (fig. 3.6). During the impregnation the temperature in the autoclave dropped but the temperature in the bag remained nearly constant due to the insulating effect of the evacuated breather between the inner and outer bag.

After impregnation the pressure was raised to consolidation pressure (e. g. 50 psi or 100 psi) and the lay-up was held at 176°F (80°C) for 20 min. At this temperature the resin maintains low viscosity, which allowed further fiber wet-out as well as easy flow of the surplus resin into the resin trap.

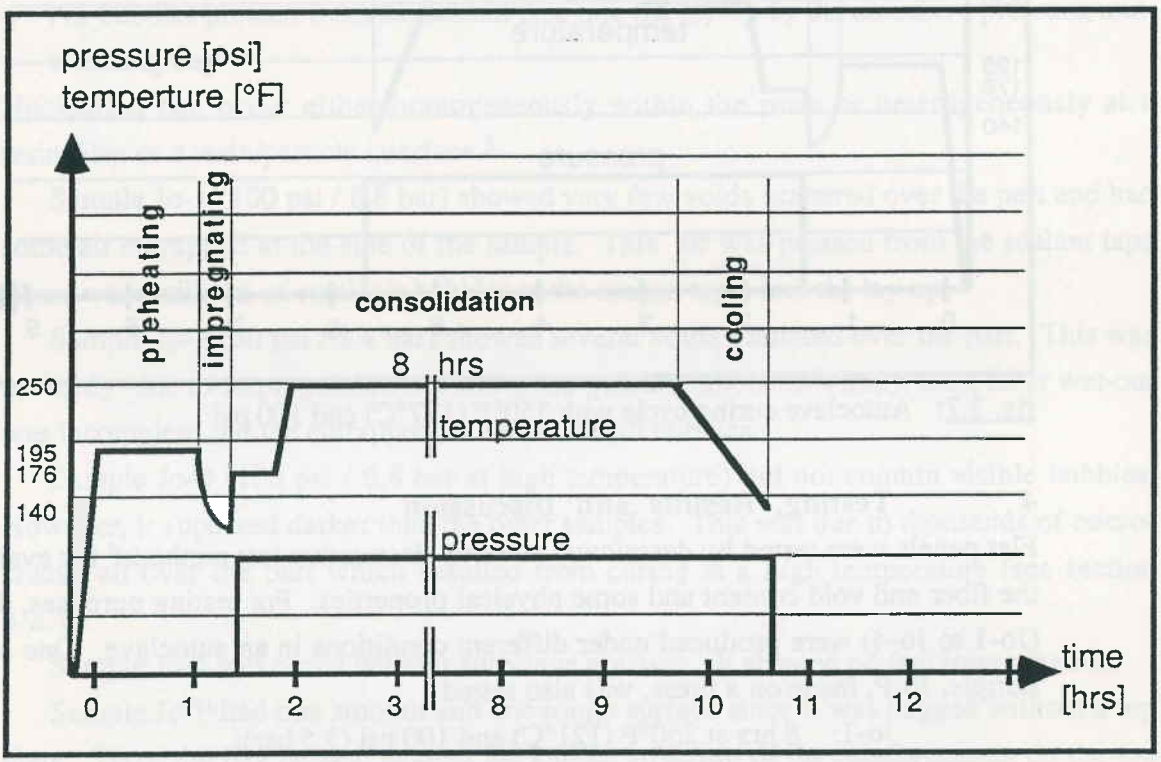



fig. 3.6: Curing cycle with 250°F (121°C)

Best results were achieved when the parts were cured for 8 hrs at 250°F (121°C) and then cooled down to 140°F (60°C) with a rate of 2°F/min (1.1°C/min) (fig. 3.6). The slow cooling rate was chosen in order to avoid thermal stresses in the laminate which would have led to distortions. This cycle was also used for T-profiles and tubes.

The 350°F (177°C) cure cycle was similar to the 250°F cure cycle. Instead of 8 hrs at 250°F the part was cured in two steps: 1 hr at 250°F followed by 1.5 hrs at 350°F. Then it was cooled down at 2.5°F/min (fig. 3.7).

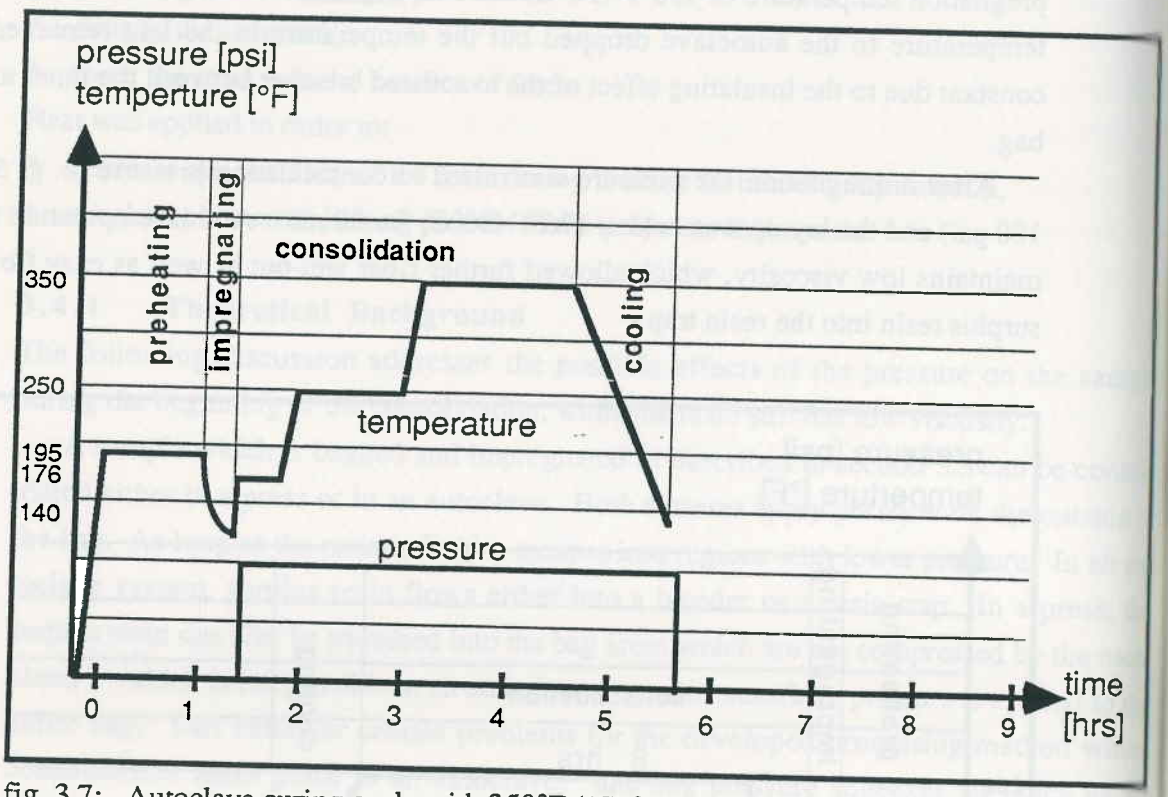



fig. 3.7: Autoclave curing cycle with 350°F (177°C) and 100 psi

## 4 Testing, Results and Discussion

Flat panels were tested by destructive and non-destructive test methods[4] for evaluation of the fiber and void content and some physical properties. For testing purposes, 4 samples (Jo-1 to Jo-4) were produced under different conditions in an autoclave. One additional sample, Jo-P, made on a press, was also tested.

Jo-1: 8 hrs at 250°F (121°C) and 100 psi (3.5 bar);
Jo-2: 8 hrs at 250°F (121°C) and 50 psi (7 bar) (no vacuum in outer bag);
Jo-3: 1 hr at 250°F (121°C) plus 1.5 hrs at 350°F (176°C) and 100 psi (7 bar);
Jo-4: 8 hrs at 250°F (121°C) and 0 psi (0 bar);
Jo-P: 3.5 hrs at 350°F (176°C) and 150 psi (bagged with no top plate).

The samples did not show distortions but the thickness across the parts varied within a range of $< \pm 5\%$. The center parts of the samples were always the thickest areas. This may have been due to the flexibility of the aluminum mold plates.

## 4.1 Visual Testing

Visual inspections of the samples were conducted against a light box which made the knitted structure visible. Areas where several bundles of fibers lay over each other appeared a little darker than those areas where the part thickness consisted only of epoxy resin. Voids appeared as dark spots in the yellow-green epoxy matrix.

Voids can be formed either by entrapment of air or by one of two nucleation processes. Entrapment could include:

- Entrapped air bubbles from the resin mixing operation (which is excluded since the resin was degassed before impregnation);
- Bridging voids from large particles or particle clusters;
- Voids from wandering fuzz balls from the breather;
- Air pockets and wrinkles created during lay-up;
- Air bubbles pressed from the sealant tape into the lay-up by the autoclave pressure, and
- a leaking bag.

Nucleation can occur either homogeneously within the resin or heterogeneously at a resin/fiber or a resin/particle interface.[5]

Sample Jo-1 (100 psi / 6.8 bar) showed very few voids scattered over the part and had some air entrapped at the side of the sample. This air was pressed from the sealant tape (there were millions of small air bubbles in the sealant tape) into the lay-up.

Sample Jo-2 (50 psi / 3.4 bar) showed several voids scattered over the part. This was probably due to impregnation occurring too quickly (about 3-4 min), thus, fiber wet-out was incomplete and the entrapped air formed small bubbles.

Sample Jo-3 (100 psi / 6.8 bar at high temperature) did not contain visible bubbles. However, it appeared darker than the other samples. This was due to thousands of micro-cracks all over the part which resulted from curing at a high temperature (see section 4.2.1).

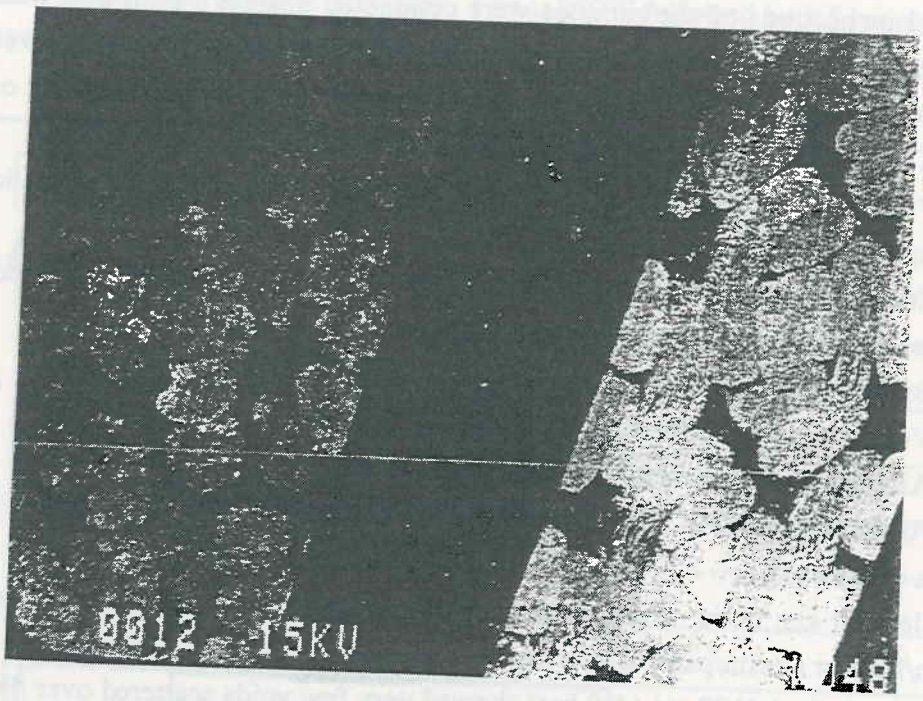
Sample Jo-4 was cured without autoclave pressure. It showed perfect impregnation.

Sample Jo-P had one smooth and one rough surface since it was bagged without a top plate. Thus, the bag nestled against the knitted structure of the reinforcement on the top part side. Jo-P showed the same micro-cracks as sample Jo-3 because it was also cured at a high temperature (350°F/176°C).

## 4.2 Physical Properties

### 4.2.1 Micro Structure

The micro structure of the samples was examined by Scanning Electron Microscopy (SEM) (Jeol / JSM-IC 848). Polished cross sections were sputter coated with gold and examined under a 15 kV accelerating voltage.




Jo-2 (50 psi / 3.4 bar)

Jo-1 (100 psi/ 6.8 bar)


Jo-4 (0 psi / 0 bar)

Jo-3 (100 psi/ 6.8 bar at 350°F/176°C cured)

fig. 4.1 : Cross sections of samples Jo-1 to Jo-4 in course direction

Fig. 4.1 shows the cross sections of sample Jo-1 to Jo-4 along the courses of the knitted reinforcement at 12x magnification. The 100 psi (6.8 bar) consolidated samples Jo-1 and Jo-3 show similar fiber volume, whereas Jo-2 (50 psi / 3.4 bar) shows a lower fiber volume. Sample Jo-4, which was cured without pressure, the 4 layers of the laminate are obviously not interlocked. With higher consolidation pressure, the interlocking effect between the layers increases as shown in sample Jo-2 (50 psi) and Jo-1 (100 psi). Sample Jo-3 shows micro cracks appearing as dark or white crescents shown more clearly in fig. 4.2 at 75x magnification. Since no cracks were found in Jo-1, Jo-2, and Jo-4, they must result from the higher cure temperature of 350°F (176°C) compared to 250°F (121°C) cure temperature for the other parts.

The reason for cracking may be due to the difference in the thermal expansion between glass ($5*10^{-6}$/K)[6] and epoxy (5 to $8*10^{-5}$/K)[7] as well as the shrinkage of epoxy during curing (1% - 3%)[6] and the brittleness due to the high temperature curing.[8] Therefore, the visible cracks are observed between the bundles of fibers since these areas are filled with resin and shrinkage cannot be hindered by the fibers. There may also be cracks or delamination at the fiber/resin interfaces, but these were not observed by SEM micrographs.

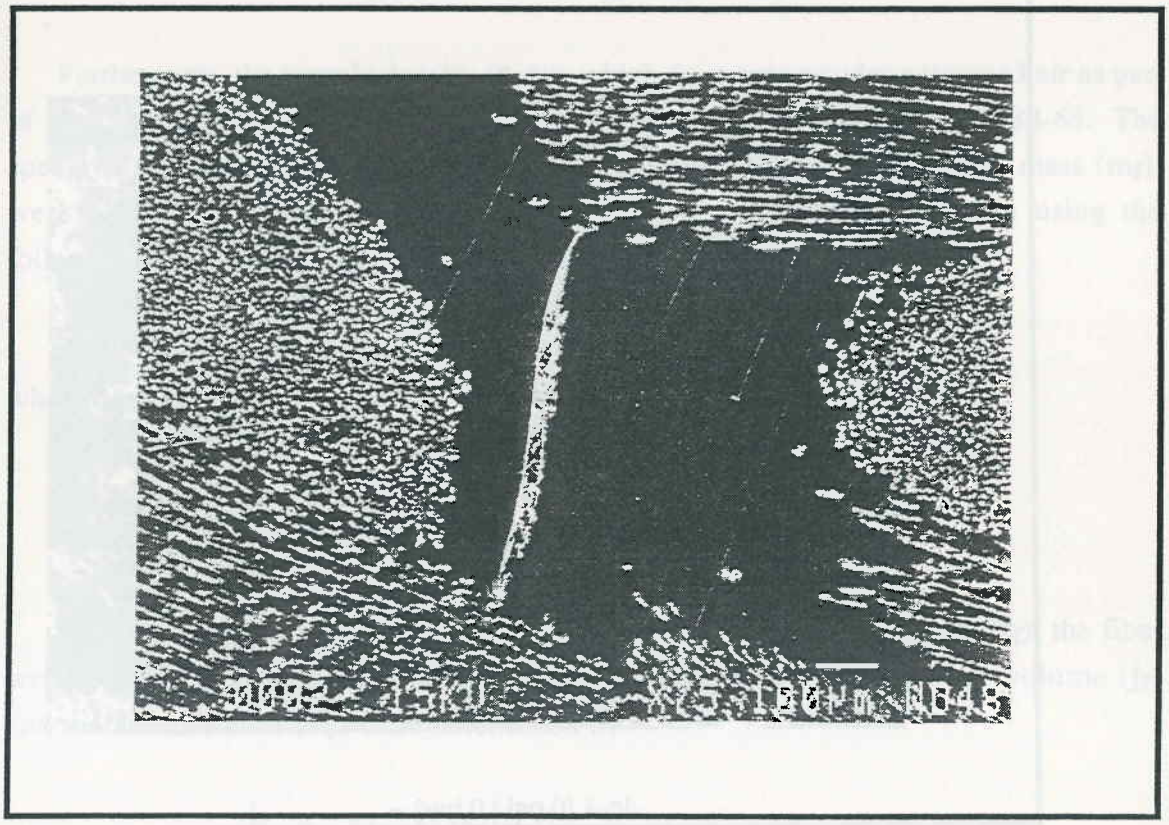
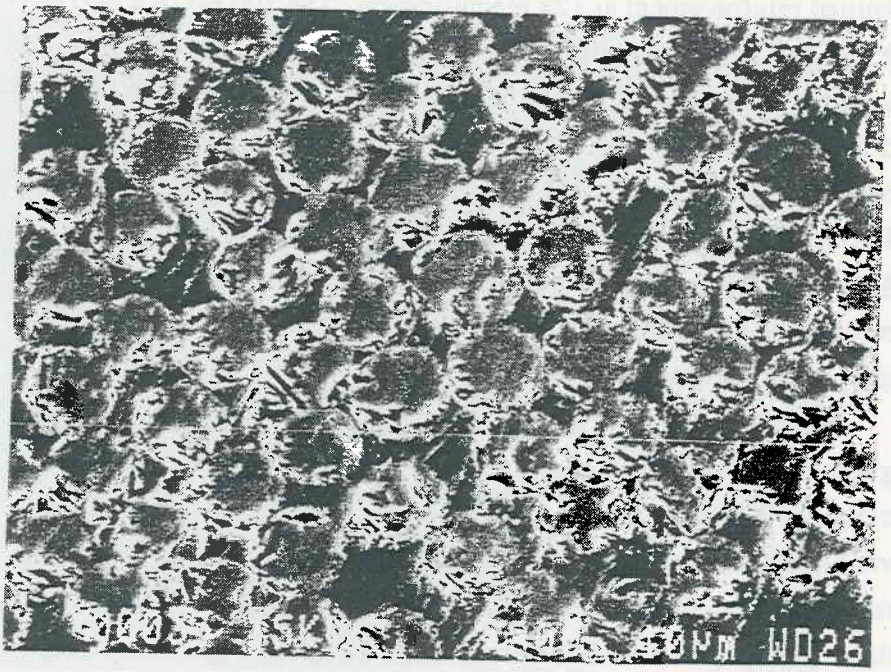
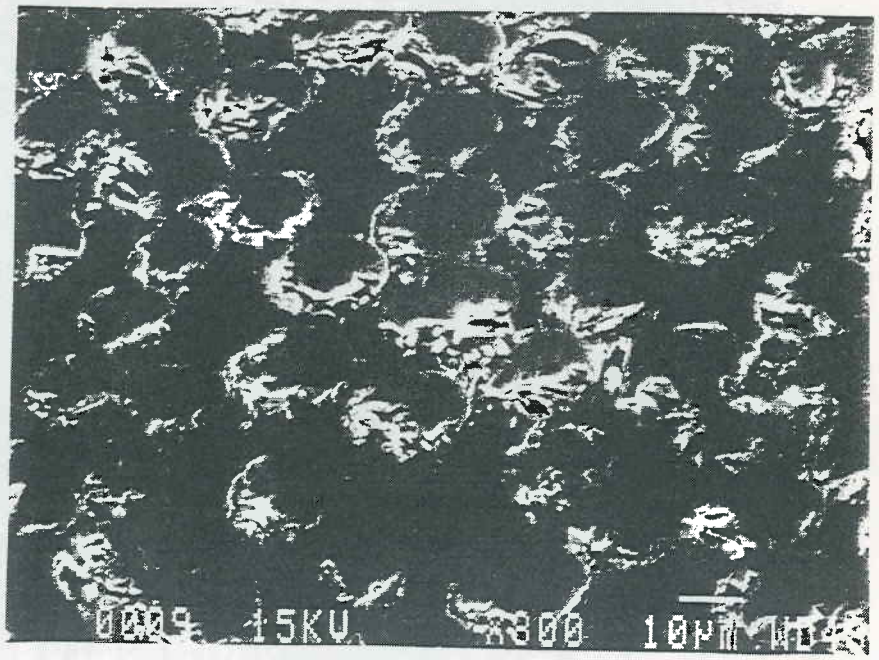


fig. 4.2: Micro cracks in sample Jo-3 (cured at high temperature) at 75x magnification



Jo-1 (100 psi / 6.8 bar)



Jo-4 (0 psi / 0 bar)

fig. 4.3 : Cross sections of samples Jo-1 and Jo-4 at 800x magnification

The quality of fiber wet-out and adhesion between fibers and matrix can be seen in fig. 4.3 which shows the cross sections of samples Jo-1 (100 psi / 6.8 bar) and Jo-4 (no pressure applied during curing) at 800x magnification. The fiber break-outs are mainly in the polish direction due to the polishing process. Resin is apparent everywhere between the single fibers and even in the close fiber bundles of sample Jo-1. Thus, fiber wet-out is satisfactory.

### 4.2.2 Fiber Volume and Void Volume

The determination of the void volume ($v_v$) is described in ASTM D2734-70. Therefore, the real specific density of the sample ($\rho_{sreal}$), which considers entrapped air as part of the sample, was determined by *fluid displacement* according to ASTM D792. The sample mass ($m_s$) and the weight of the sample ($m_{s'}$) in a liquid of known density ($\rho_F$) was determined. Freon (1,1,2-Trichloro-1,2,2-trifluoroethane) was used as the liquid because of its low surface tension. The density of Freon was determined experimentally to be $\rho_F$ = 1.562 g/cm$^3$ at 23.5°C. The real density of the specimen ($\rho_{sreal}$) was calculated using the following relation:

$$\rho_{sreal} = \rho_F * m_s / (m_s - m_{s'})$$

Furthermore, the sample density ($\rho_{sdet}$), which does not consider entrapped air as part of the sample, was determined by loss on ignition according to ASTM D 2584-68. The specimen's mass before ignition ($m_s$) and the mass of its residue, the fiber mass ($m_f$), were used to calculate a **determined density** ($\rho_{sdet}$) of the specimen using the following equation:

$$\rho_{sdet} = 1 / (y_r * \rho_r + y_f * \rho_f)$$

| | | | |
|---|---|---|---|
| wherein | $y_f$ = | $m_s/m_f$ | **fiber weight content,** |
| | $y_r$ = | $(m_s-m_f)/m_s$ | **resin weight content,** |
| | $\rho_f$ = | 2.54 g/cm$^3$ | **fiber density** (E-glass),[9,10] |
| | $\rho_r$ = | 1.2003 g/cm$^3$ | **cured resin density.**[3] |

With the determined density ($\rho_{sdet}$) of the specimen, the fiber density ($\rho_f$), the fiber weight content ($y_f$) and the real density ($\rho_{sreal}$) of the specimen, the **fiber volume** ($j_f$) and the **void volume** ($v_v$) were determined by

$$j_f = y_f * (\rho_{sdet}/\rho_f).$$
$$v_v = (1 - \rho_{sreal}/\rho_{sdet}).$$

Of each of the samples Jo-1 to Jo-4, five specimens were taken from areas which visually appeared bubble-free and fiber and void volumes for each were determined (tab. 4.1). Additionally, one sample (Jo-P) was consolidated on a press with 150 psi (10.2 bar) at 350°F (176°C) for 3.5 hrs.

| | Jo-1 | Jo-2 | Jo-3 | Jo-4 | Jo-P |
|---|---|---|---|---|---|
| $j_f$[%] | 58.64±0.81 | 54.45±0.63 | 60.03±0.54 | 35.45±0.19 | 66.47±0.76 |
| $v_v$[%] | -0.13±0.1 | -0.006±0.05 | 0.6±0.28 | 0.38±0.07 | 0.71±1.73 |

tab. 4.1: Fiber and void volumes

The results show that the fiber volume increases with the applied consolidation pressure. 50 psi (Jo-2) pressure leads to a fiber volume of about 55%, whereas 100 psi (Jo-1 and Jo-3) yields about 59%. Sample Jo-P (cured in a press at 150 psi (10.2 bar)) has a fiber volume of 66.5%. The high pressure and the absence of a top plate led to the higher fiber volume. If a top plate had been used the areas between the knitted pattern of the sample and the top plate would have been filled with additional resin. Thus, the fiber volume would be lowered which would have a larger effect on thin samples than on thick samples. This observation leads to the conclusion that thicker samples with smooth surfaces will possess a higher fiber volume than similar thin samples.

All tested parts contained less than 1% voids. Negative void volumes were determined for samples Jo-1 and Jo-2, but they were very close to 0% within experimental error. Therefore, those void volumes are regarded as 0%.

Sample Jo-3 contained 0.7% voids as did sample Jo-P. This is due to the micro cracks (section 4.2.1) resulting from high temperature curing at 350°F (176°C). Sample Jo-4 contained 0.3% voids. This sample which was cured without pressure applied did not show any air bubbles visually or under the SEM. The air must be desolved in the resin eventhough the steps, 'preheating and evacuating of the reinforcement' as well as 'degassing the resin' are supposed to eliminate both air and moisture entirely prior to impregnation.

## 4.3 Chemical Properties - Curing Status of the Resin

It was desired to achieve a short cure cycle. This requires high cure temperature in order to catalyze the cross-linking process of the epoxy resin and the curing agent. The higher the extent of polymerization, the higher the heat-resistance of the resin, but the brittleness of the cured resin also increases. High heat-resistance is desired, whereas a ductile matrix is preferred. Thus, a compromise between both properties has to be

achieved by adjusting curing temperature and cure time to an optimum.[6] However, as discussed earlier (section 4.2.1), the recommended curing temperature of 350°F was too high because it led to internal stresses causing cracks in the laminates from the knit structures.

The samples were tested on their curing status with a Differential Scanning Calorimeter (DSC) (Model 901 / DuPont Instruments). The DSC was usaed to determine the glass transition temperatures (GTT) of the cured resin as a measure of its heat capacity using a ramp rate of 10°C/min (5.55°F/min) according to ASTM D3418-82.

The GTTs of unaccelerated epoxy resin cured at 250°F (121°C) and 350°F (176°C) given by the manufacturer are shown in tab. 4.2. The GTTs of sample Jo-1 to Jo-4 and Jo-P determined with DSC are given in tab. 4.3.

| | 0.5 hrs | 1.5 hrs | 2.5 hrs | 4 hrs | 8 hrs |
|---|---|---|---|---|---|
| at 250°F | | | | 235 (130) | 273 (134) |
| at 350°F | 266 (130) | 302 (150) | 322 (161) | | |

tab. 4.2: Glass transition temperatures [°F (°C)] of EPON Resin DPL-862 cured with Curing Agent W at 250°F and 350°F according to the manufacturer[2]

| | 0.5 hrs | 1.5 hrs | 2.5 hrs | 3.5 hrs | 8 hrs |
|---|---|---|---|---|---|
| at 250°F | | | | | 263 - 270 |
| at 350°F | | 284 (140) | | 288 (142) | |

tab. 4.3: Glass transition temperatures [°F (°C)] of tested samples

The experimental data from the samples agree closely to those reported by the manufacturer. The slight difference between the data might result from a different ramp rate used in the manufacturer's DSC tests. For future manufacturing it might be suitable to cure the parts at 250°F for 4 hrs and then post cure them for 0.5 hrs at 350°F. If microcracks do not appear, this cure procedure would reduce the cure time by almost 50%.

## 4.4 Mechanical Properties: Tensile Tests on Flat Panels

Knits have a relatively loose structure. Thus, the mechanical properties of composites made from knit structures are not expected to have the same characteristics as composites made of woven fabrics. However, tensile tests were carried out on flat panels to verify whether the new developed procedure for manufacturing composites leads to parts with properties equal to existing results of other researchers working with knit structures.[1]

Tensile test for fiber-resin laminates of symmetric, orthotropic construction are standardized in ASTM D3039-76. According to this method, test specimens have a constant cross section with tabs bonded to the ends. The test specimens, however, were

shaped as a dog-bone according to ASTM E8-92 (test method for metallic materials). The average thicknesses T of the tested specimens met the requirements of ASTM D3039-76 for fiber-resin laminates:

$T_{Jo-1}$ = 0.137" (3.37 mm);
$T_{Jo-2}$ = 0.144" (3.65 mm);
$T_{Jo-3}$ = 0.135" (3.42 mm);
$T_{Jo-4}$ = 0.208" (5.28 mm).

The tests were carried out on Instron 1125. The crosshead speed for a grip distance of 4" (101.6 mm) was set to 0.059 in/min (1.5 mm/min) in order to create a strain rate of 0.015 in/in*min as recommended in ASTM D3039. The gage length was set to the grip distance taking into account that the results in strain would not be accurate due to the increasing width at the specimen ends. Accordingly, the true strain rate in the narrowed section was actually a little higher than the measured strain rate. Thus, the actual Young's Modulus is expected to be a little lower than the measured values (tab. 4.4). However, the measured strength referred to the narrowed section, thus, those results are representative for evaluation of the quality of the implemented manufacturing procedure.

The specimens were tested in the wales direction (0°) of the reinforcement's knit structure. Plots of the averages (average of five specimen) of the tensile test results of samples Jo-1 to Jo-4 with stress [MPa] versus strain [%] are shown fig. 4.4.

As can be seen in fig. 4.4 and fig. 4.5, sample Jo-1 to Jo-4 have the same general behavior. During approximately the first 30% of the maximum strain, the composite showed elastic behavior which was slightly degressive. During the following 10% to 20% of the tensile test, the matrix began to fail in horizontal cracks across the specimen (course direction) resulting in several small stress peaks on the plot. Some cracks (peaks on the plot), however, occurred later in the regions of the wider sections at the specimen's ends. Broken loops of the knitted structure were visible in the break surface.

The cracking behavior was very obvious on specimens of sample Jo-4 which was cured without pressure applied. The single layers were not interlocked with each other as they were in the densified samples (fig. 4.1). The cracks and the break occurred in the loop areas of the knitted fabric because there were no longitudinal fibers which could bear the load.

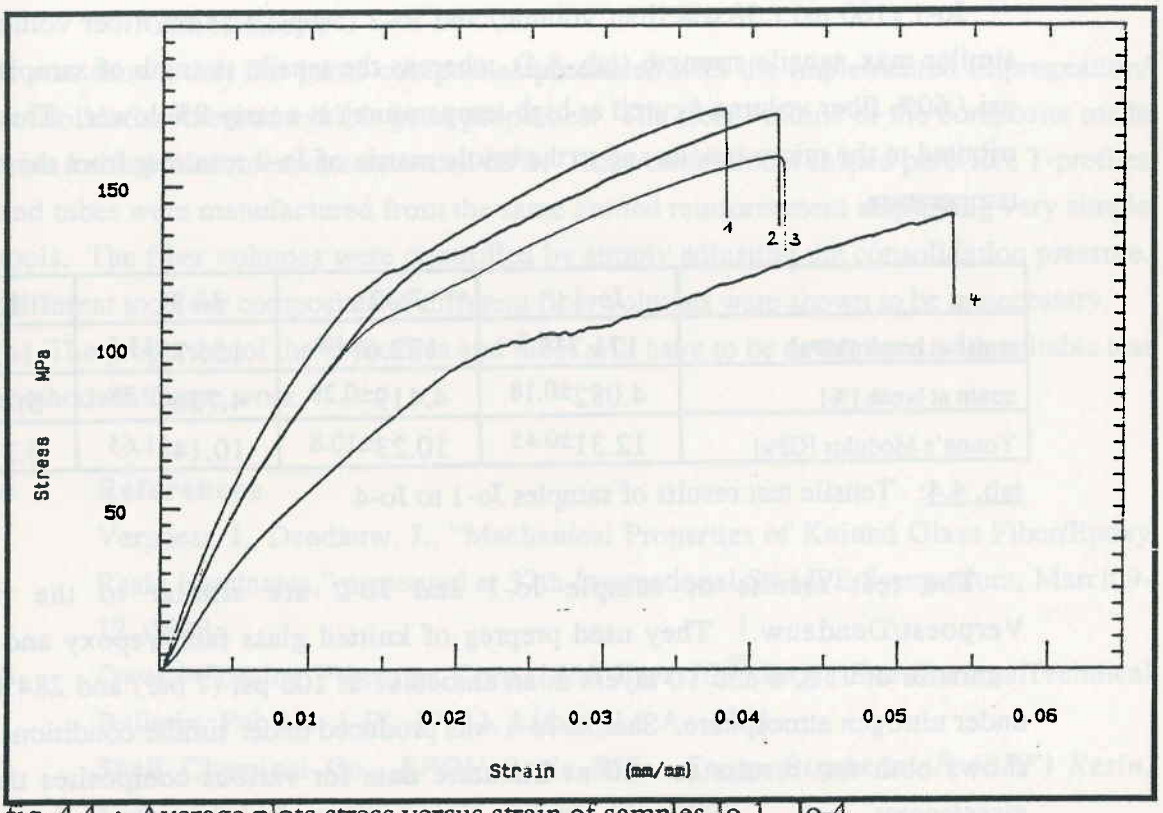



fig. 4.4 : Average plots stress versus strain of samples Jo-1 - Jo-4

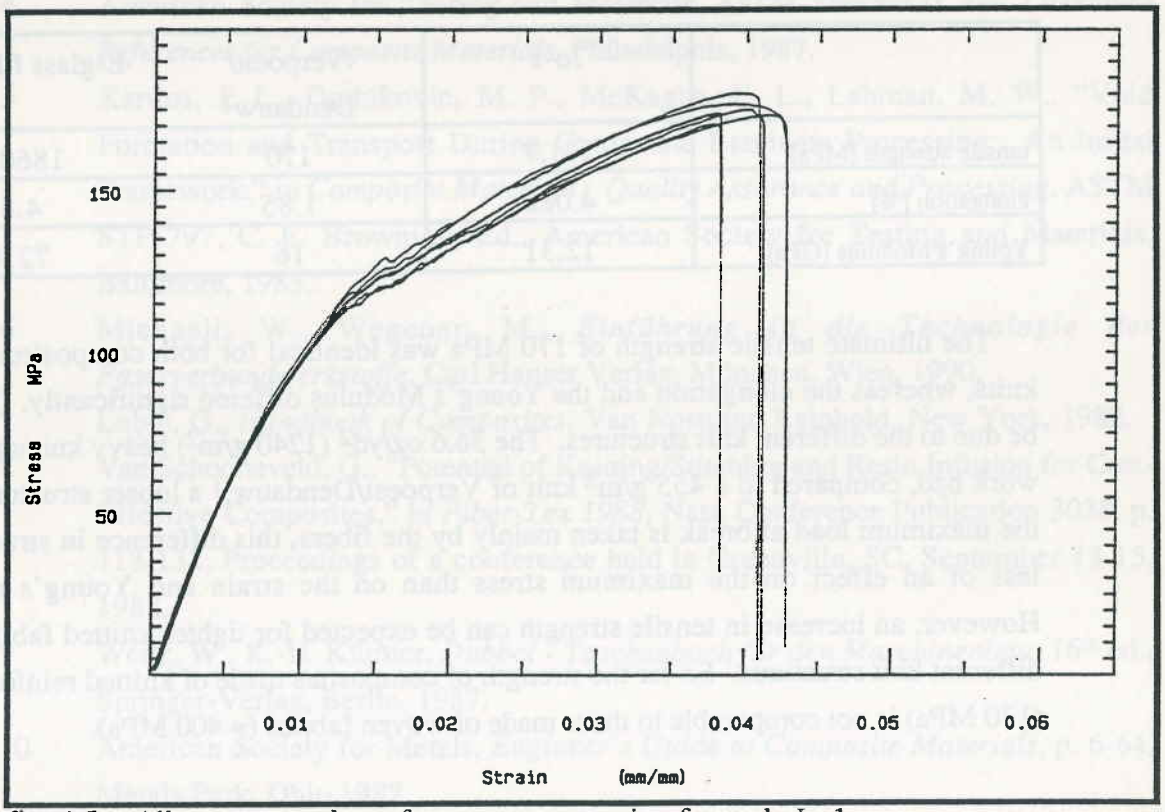



fig. 4.5 : All + average plots of stress versus strain of sample Jo-1

Jo-1 (100 psi / 58.6% fiber volume) and Jo-2 (50 psi / 54.5% fiber volume) show similar max. tensile strength (tab. 4.4), whereas the tensile strength of sample Jo-3 (10 psi / 60% fiber volume / cured at high temperature) is nearly 9% lower. This can be attributed to the micro-cracks and to the brittle matrix of Jo-3 resulting from the high curing temperature.

| | Jo-1 | Jo-2 | Jo-3 | Jo-4 |
|---|---|---|---|---|
| stress at break [MPa] | 171.7±6.3 | 172.6±4.8 | 155.7±13.5 | 143.4±3.8 |
| strain at break [%] | 4.082±0.18 | 4.419±0.29 | 4.736±0.38 | 5.788±0.29 |
| Young's Modulus [GPa] | 12.31±0.45 | 10.23±10.8 | 10.14±1.65 | 6.313±0.52 |

tab. 4.4: Tensile test results of samples Jo-1 to Jo-4

The test results of sample Jo-1 and Jo-2 are similar to the results of Verpoest/Dendauw.[1] They used prepreg of knitted glass fabric/epoxy and produced laminates of 1, 3, 6 and 10 layers in an autoclave at 103 psi (7 bar) and 284°F (140°C) under nitrogen atmosphere. Sample Jo-1 was produced under similar conditions. Tab. 4.5 shows both test results as well as literature data for various composites made of E-glass/epoxy.

| | Jo-1 | Verpoest/ Dendauw[1] | E-glass fiber [2,11] |
|---|---|---|---|
| tensile strength [MPa] | 171.7 | 170 | 1860.3 |
| elongation [%] | 4.082 | 1.85 | 4.8 |
| Young's Modulus [GPa] | 12.31 | 16 | 72.4 |

The ultimate tensile strength of 170 MPa was identical for both composites made of knits, whereas the elongation and the Young's Modulus differed significantly. This may be due to the different knit structures. The 36.6 oz/yd$^2$ (1240 g/m$^2$) heavy knit used in this work had, compared to a 455 g/m$^2$ knit of Verpoest/Dendauw,[1] a looser structure. Since the maximum load at break is taken mainly by the fibers, this difference in structure had less of an effect on the maximum stress than on the strain and Young's modulus. However, an increase in tensile strength can be expected for tighter knitted fabrics or for different knit structures. So far the strength of composites made of knitted reinforcements (170 MPa) is not comparable to those made of woven fabrics (≈ 400 MPa).

## 5 Conclusions

It was shown that flat panel composites processed with the implemented impregnation/ consolidation method exhibit good properties. The fiber volume of the composite made from knitted reinforcements exceeded 60%. Three-dimensional shaped parts like T-profiles and tubes were manufactured from the same knitted reinforcement employing very simple tools. The fiber volumes were controlled by simply adjusting the consolidation pressure. Different tools for composites of different fiber volumes were shown to be unnecessary.

The properties of the T-profiles and tubes will have to be determined with suitable test methods in future work.

## 6 References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