PROCESS SIMULATION OF MULTIPLE MATERIAL FILAMENT WOUND PIPES

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SUMMARY: A model for wet filament winding has been extended to enable process simulation of advanced pipe structures consisting of multiple materials. The extension includes treatment of different coefficients of thermal expansion in glassy and rubbery state and use of multiple materials. A common problem in wet filament winding manufacturing is the occurrence of delaminations. Two basic types of delamination modes have been identified by out-of-plane tensile testing of flat laminates. These modes have been assumed to also exist in pipes. The test results have been used together with the process model to control the manufacturing process and eliminate delamination problems in pipe structures. Analysis of five manufacturing cases are presented. Three of these cases had delamination problems in production which were all solved by use of process simulations.

KEYWORDS: Process model, filament winding, delamination.

INTRODUCTION

SICOMP has developed a process model and process simulation tool for wet filament winding based on work by Lee [1]. Demands from the URENCO (Capenhurst) company has led to extensions of the current model to handle process simulation of advanced pipe structures consisting of multiple materials. The process simulation tool called WetWind, has been used by the URENCO (Capenhurst) company during the last four years.

MODEL

Multiple Materials

The process model has previously been described in [2, 3]. It has now been extended to enable process simulation of the manufacture of multiple material filament wound pipes. It can now simulate wet filament winding manufacturing of advanced pipe structures consisting of up to 5 fiber types, 2 resin systems, isotropic materials and special materials.

Matrix Thermal Expansion Coefficient

After gelation the matrix is transformed into a solid material. This material occurs in three forms, rubbery, transition and glassy state depending on temperature and degree of cure, see Fig. 1. The matrix thermal expansion coefficient in the fluid material state is much higher ($210 \cdot 10^{-6}$ 1/°C) than the fully cured matrix thermal expansion coefficient in glassy material state ($69 \cdot 10^{-6}$ 1/°C) according to data from the supplier of the epoxy used. Measurements on a similar bisphenol A resin (Shell Epikote 828) was made in [4]. Obtained values for the cured matrix thermal expansion coefficient was $86 \cdot 10^{-6}$ 1/°C for the glassy region and $220 \cdot 10^{-6}$ 1/°C for the rubbery region. The material model has hence been modified to take this effect into account. A simpler model for the same effect was furthermore used in [5].

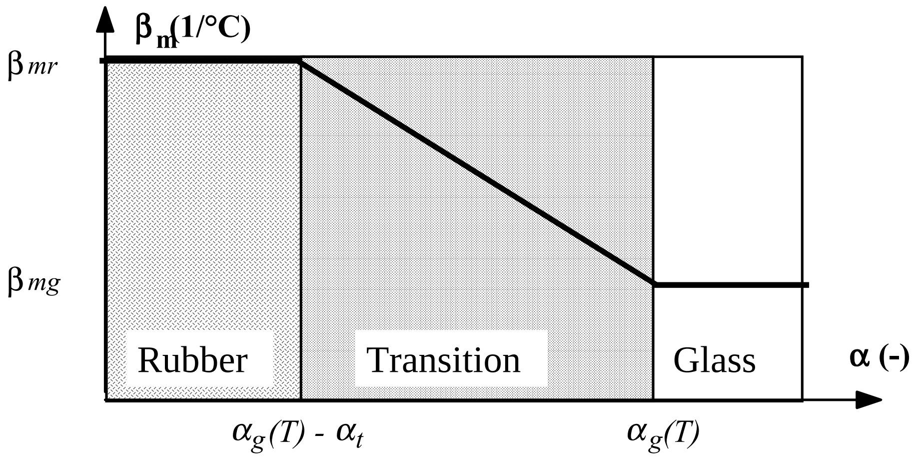

Fig. 1: Matrix thermal expansion coefficient as a function of solid material state

The transition from rubbery state to glassy state is controlled by the curing reaction and temperature. The transition depth α_t is modelled as a constant in the degree of cure. In [6] an α_t of 0.08-0.12 was achieved for the isothermal cure of the epoxy at varying temperatures. In [4] an α_t of 0.1 was achieved during cool down from full cure. [4] indicates that the thermal expansion coefficient is fairly constant in the glassy and rubbery region respectively with a rather linear transition behaviour. The material parameters in the model are calculated locally in the pipe. The matrix thermal expansion coefficient in solid state β_m is described by Eqn 1 and 2 as

$$\beta_m = \beta_{mr} \text{ for } \alpha \leq \alpha_g(T) - \alpha_t,\ \beta_m = \beta_{mg} \text{ for } \alpha \geq \alpha_g(T) \qquad (1)$$

$$\beta_m = (\beta_{mg} - \beta_{mr})(\alpha - \alpha_g(T))/\alpha_t + \beta_{mg}, \text{ for } \alpha_g(T) - \alpha_t < \alpha < \alpha_g(T) \qquad (2)$$

for $\alpha_{gel} \leq \alpha \leq 1$

where α is the degree of cure and α_{gel} is the degree of cure at completed gelation. The degree of cure when glass transition occurs α_g(T) is a function of temperature and is obtained from the reaction kinetics. β_{mg} is the matrix thermal expansion coefficient in the glassy state. β_{mr} is the matrix thermal expansion coefficient in the rubbery state. Subscript *m* denotes the matrix, *r* the rubbery state and *g* the glassy state.

Calculation Data

Material properties for CIBA epoxy system LY556/HY917/DY070 have been used in all calculations. The material data used is similar to [3]. A matrix volume shrinkage after completed gelation of 3.4 % and an α_{gel} of 0.35, are indicated by SICOMP measurements and these values have been used in all the calculations. The new material model for the matrix thermal expansion has been used instead of the approximation $\beta_m = \beta_{mg}$ after completed gelation used previously [1, 2, 3]. This mechanism has a large effect since it decreases the residual stress by 10-15 %. See Table 1 for some of the material data. The main process data is described for each case studied. R_o^{ma} is the mandrel outer radius, h_{tot} is the layup thickness, ϕ is the layup ± winding angle, σ_f^0 is the initial fiber roving tension, *Type* is the fiber type (E = E-glass, C = carbon fiber and Roh = Rohacell core material), t is the oven cure time and T_{cure} is the oven cure temperature. To avoid mandrel-composite contact problems all calculations have been performed with the mandrel locked to the composite until the final mandrel release, after completed manufacture.

Table 1: Material data

β_{mr} (1/°C)	β_{mg} (1/°C)	α_t (-)	α_{gel} (-)
$200 \cdot 10^{-6}$	$69 \cdot 10^{-6}$	0.1	0.35

DELAMINATION

Modes

It has been assumed that two basic delamination modes exist during filament winding of pipes. For both delamination modes the main controlling stress parameter is assumed to be the residual radial stress. The most likely case is delamination during cool down of the pipe from the final cure temperature. This will be referred to as delamination mode 1. The material is fully cured but the residual stress is high enough to cause delamination. The other assumed mode occurs after gelation but before full cure and hence before full strength of the material has been obtained. This will be referred to as delamination mode 2.

Testing of Laminates

Tensile strength after gelation

In a previous investigation a test rig for out-of-plane tensile testing of flat laminates according to ASTM C297 was constructed. Glass/vinylester laminates were tested to failure during cure [7]. A continuous curve for out-of-plane tensile strength versus the degree of cure was hence obtained, see Fig. 2. The material was very weak at low degrees of cure as expected. Separate experiments at SICOMP have furthermore shown that 1 Bar (vacuum) can sometimes be enough to create a delamination of composite plates at gelation, which commonly does not disappear despite further cure later in the manufacturing cycle. These test results gave a guide to typical radial strengths in pipes for mode 2.

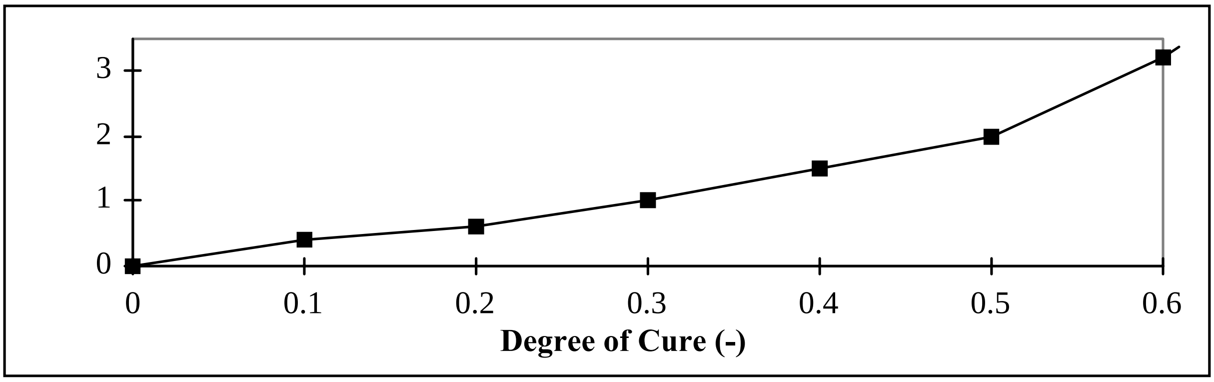

Fig. 2: Measured out-of-plane tensile strength vs. degree of cure

Tensile strength at high degrees of cure

Fully cured carbon/vinylester laminates were loaded to failure at SICOMP according to ASTM C297. Typical obtained out-of-plane tensile strength was 20 MPa. URENCO have made similar measurements on fully cured filament wound glass/epoxy and carbon/epoxy samples indicating an out-of-plane tensile strength of 30-40 MPa. A pipe does however have a much larger failure surface than these tested samples. The pipe delamination is furthermore brittle since the delamination typically propagates through the complete pipe. A typical radial strength of 25-30 MPa for mode 1 failure in pipes with the epoxy materials used seems to be in the right order of magnitude.

Thick Glass/Epoxy Pipe

Two 50 mm thick glass/epoxy pipes were manufactured at SICOMP according to Table 2. Pipe 116 was delaminated at mid thickness after manufacture while Pipe 114 was without defects. It was thought that Pipe 116 delaminated during cool down to room temperature since a sharp cracking sound had been heard.

Table 2: Process data

Pipe (-)	R_o^{ma} (mm)	h_{tot}, ϕ (mm, °)	h_{tot}, σ_f^0 (mm, MPa)	t, T_{cure} (hour, °C)
116	18	50, 89	50, 13	6, 80 + 3, 140
114	18	50, 89	50, 63	6, 80 + 3, 140

The residual tangential stress has been measured and correlated with the calculations for these two pipes. It was assumed that the failure mode was primarily dependent on the radial tensile stress. Fig. 3 shows the calculated radial stress at mid thickness for the two pipes. The drop in stress at 1450 minutes process time is created when the mandrel is released from the composite in the calculations. Delamination mode 2 can not be completely ruled out for these pipes but Pipe 116 was observed to delaminate according to mode 1. The calculated final residual stress state is in Fig. 4. Maximum residual radial stress is 29.8 MPa for Pipe 116 and 24.3 MPa for Pipe 114. The indicated radial strength of 25-30 MPa for mode 1 would explain the behaviour of the two pipes.

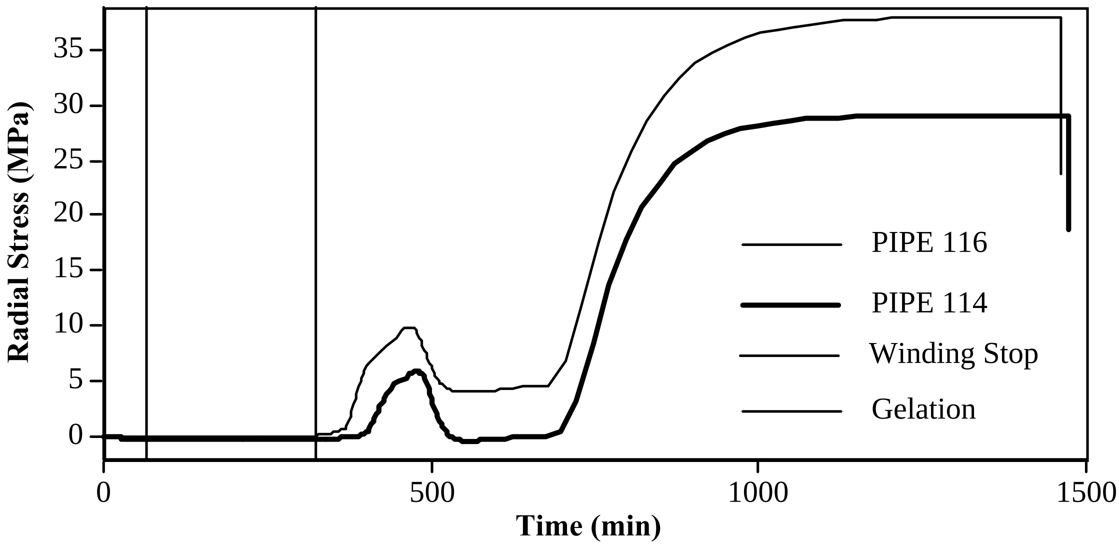

Fig. 3: Calculated radial stress at mid thickness vs. time

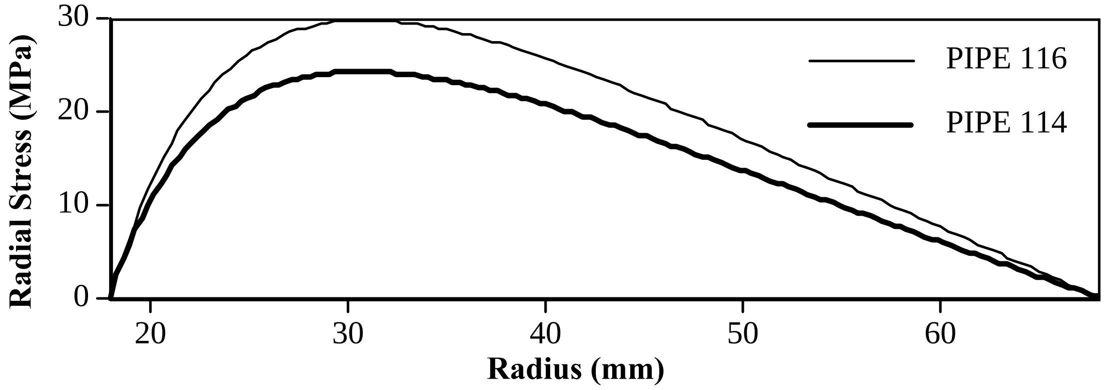

Fig. 4: Calculated residual radial stress vs. radius

Thick Glass/Epoxy Pipe Component

A 59 mm thick prototype pipe from glass/epoxy was manufactured by an industry. It repeatedly delaminated at mid thickness despite finally using a three-step winding and curing cycle. WetWind was used to analyse the pipe. Mode 1 delamination was assumed to be the problem based on previous experience. Improved processing conditions were defined assuming a radial strength of 25-30 MPa for mode 1. A higher roving tension increased the achieved fiber volume fraction from 55 % to 65 % and this along with a prolonged cure cycle at lower temperature during gelation decreased the residual radial stress, see Table 3.

Table 3: Process data

Pipe (-)	R_o^{ma} (mm)	h_{tot}, ϕ (mm, °)	h_{tot}, σ_f^0 (mm, MPa)	t, T_{cure} (hour, °C)
Original	20	59, 89	59, 13	7, 80 + 6, 140
Improved	20	59, 89	59, 63	13, 70 + 4, 85 + 4, 100 + 5, 140

Fig. 5 shows the calculated radial stress at mid thickness for the two pipes. The calculated final residual stress state is shown in Fig. 6.

The maximum residual radial stress was found to be 32.1 MPa for the original processing conditions and 28.3 MPa for the improved pipe. The improved pipe was manufactured at SICOMP, using a one-step winding and curing cycle, resulting in no delamination.

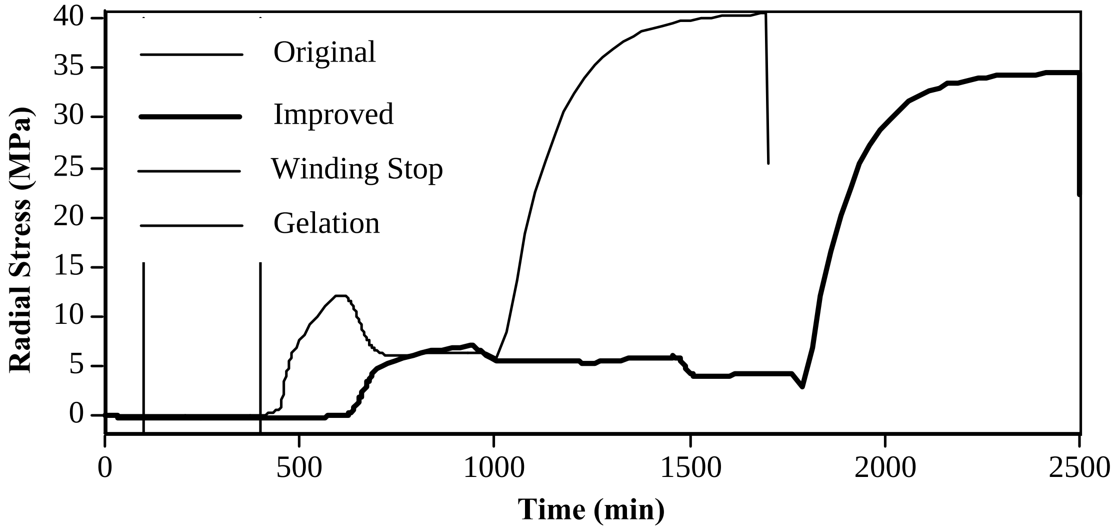

Fig. 5: Calculated radial stress at mid thickness vs. time

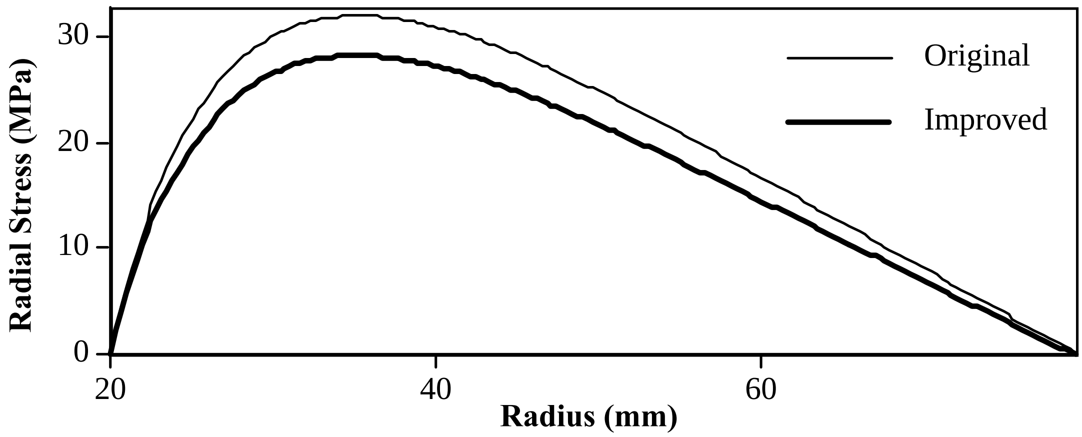

Fig. 6: Calculated residual radial stress vs. radius

Thin Glass/Epoxy Pipe

An industry had severe problems manufacturing an 8 mm thick glass/epoxy pipe. It was found to delaminate every time despite 12 different process variations, including a two-step winding and curing cycle. The pipe was analysed using WetWind. The general residual stress state was low which eliminated mode 1 as a likely failure mechanism. A radial tensile stress in the order of a few bar was however calculated after gelation at 70 °C oven temperature, which meant mode 2 failure was possible. Improved process parameters were hence calculated to minimise the radial tensile stress after gelation, see Table 4.

Table 4: Process data

Pipe (-)	R_o^{ma} (mm)	h_{tot}, ϕ (mm, °)	h_{tot}, σ_f^0 (mm, MPa)	t, T_{cure} (hour, °C)
Original	20	5, 81 + 1, 58 + 2, 81	8, 13	6, 70 + 4, 140
Improved	20	5, 81 + 1, 58 + 2, 81	8, 46	6, 70 + 4, 140

Fig. 7 shows the calculated residual radial stress state for the two pipes with negligible stress. It can be observed that the improved pipe has similar residual radial stress. Fig. 8 shows the calculated radial stress at mid thickness for the two pipes. The original pipe has a small radial tensile peak at 426 minutes process time which is likely to have caused the delamination. Fig. 9 shows the radial stress distribution at 426 minutes process time. The assumed failure mode 2 for this case was verified later when it was found that the original pipes were already delaminated (in the hot condition) after curing at 70 °C. The delamination disappeared immediately in production when the improved process parameters were used.

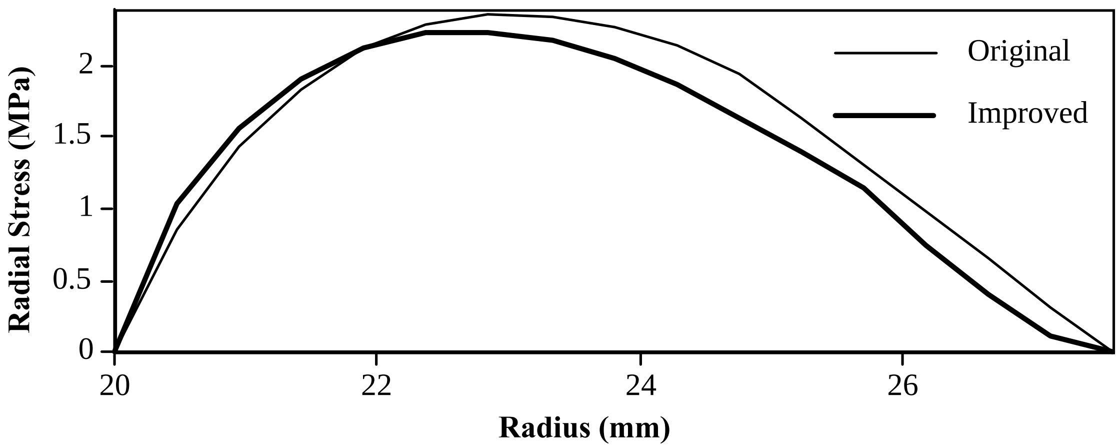

Fig. 7: Calculated residual radial stress vs. radius

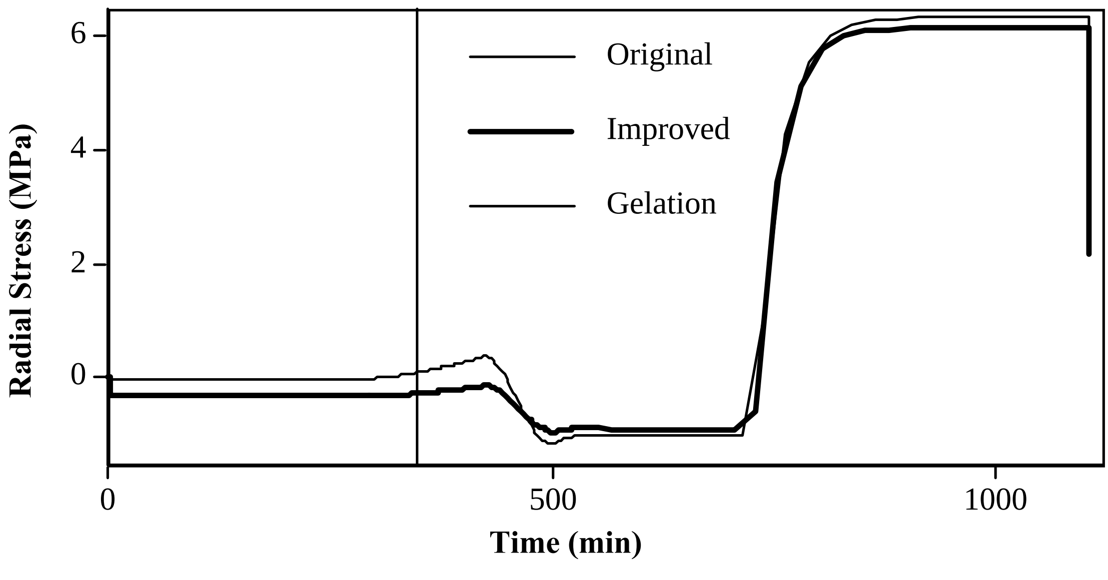

Fig. 8: Calculated radial stress at mid thickness vs. time

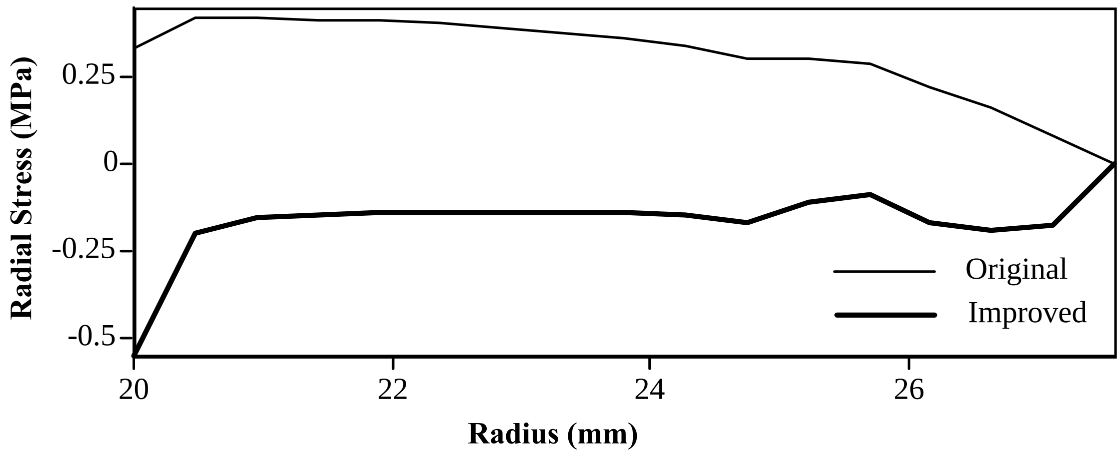

Fig. 9: Calculated radial stress at 426 minutes process time vs. radius

SIMULATION OF FLYWHEEL STRUCTURES

URENCO (Capenhurst) and SICOMP have carried out WetWind calculations on an advanced thick flywheel structure manufactured from multiple materials. The accuracy of the calculation has been tested by measuring temperature, fiber volume fraction, dimensional changes, etc. The analysis has enabled detailed analysis and understanding of the complex manufacturing process. Some basic results are presented here although it must be emphasised that URENCO (Capenhurst) have fine-tuned and improved the manufacturing beyond these results. The flywheel consists of one layer of glass/epoxy with a magnetic powder in the epoxy (denoted F), another layer of glass/epoxy and a final layer of carbon/epoxy. The process calculations have been used to choose the mandrel material, optimise the fiber roving tension profile during winding (to control the fiber fraction and reduce the residual stress), optimise the sophisticated cure cycle which controls the heat flow from the mandrel and outer composite and uses the flywheel itself as a heat sink, test new materials and new ideas and solve manufacturing problems. Fig. 10 shows the final fiber volume fraction for one calculated case. Fig. 11 and Fig. 12 show the corresponding residual stress state. It can be observed that the calculated residual radial stress with a maximum value of 18.3 Mpa, is fairly low despite the thickness and complexity of the structure.

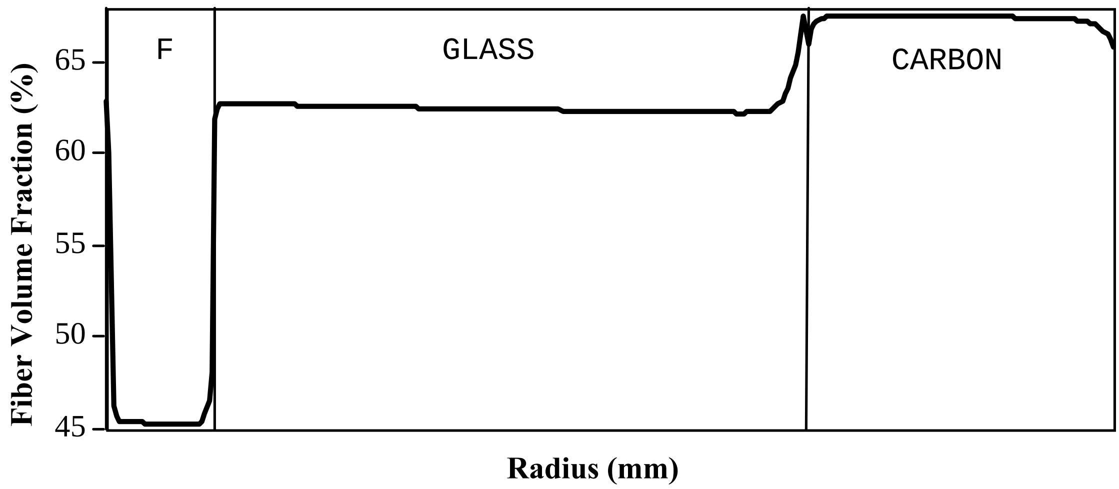

Fig. 10. Calculated final fiber volume fraction vs. radius for flywheel.

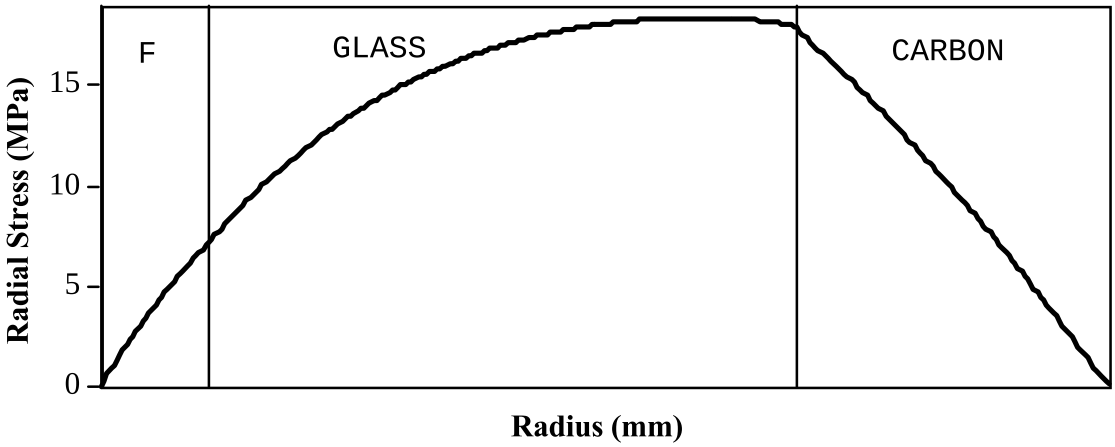

Fig. 11: Calculated residual radial stress vs. radius for flywheel

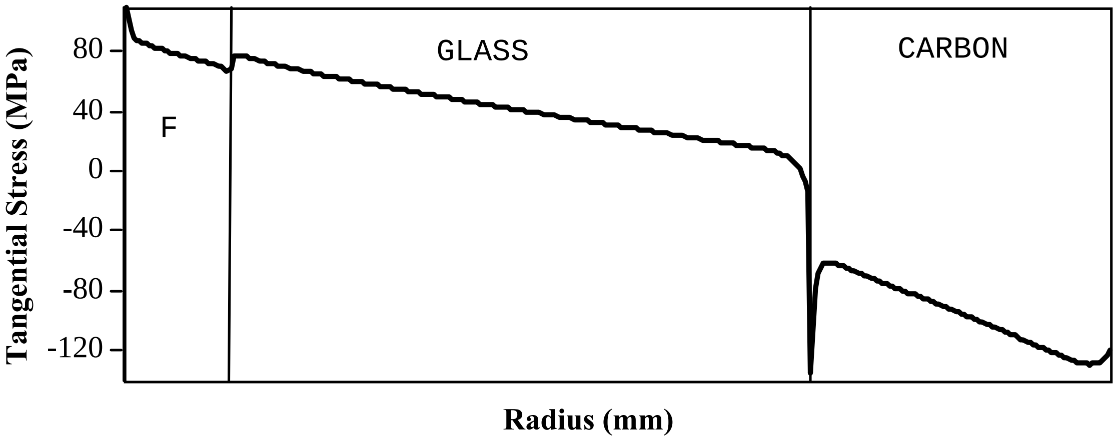

Fig. 12: Calculated residual tangential stress vs. radius for flywheel

SIMULATION OF A SANDWICH PIPE

SICOMP have manufactured a 15 mm thick sandwich structure made from carbon/epoxy/rohacell in a one-step process. The main layup angles used for the carbon are given in Table 5. Initially there were some delamination problems at the core/carbon interface so some process calculations were made. Fig. 13 shows the calculated residual radial stress and Fig 14 the residual tangential stress. The stress state is fairly low. The sandwich pipe essentially seems to behave like two thin-walled carbon/epoxy pipes (inner- and outer carbon/epoxy layer). One important aspect is to control the cure cycle so both the carbon layers are cured despite the thermal insulation effect from the core material. The delamination problems were traced to irreversible deformation of the core material at 120 °C and solved by using another core material.

Table 5: Process data for sandwich pipe

R_o^{ma} (mm)	h_{tot}, ϕ (mm, °)	h_{tot}, σ_f^0 (mm, MPa)	h_{tot}, Type (mm, -)	t, T_{cure} (hour, °C)
185	2, 15 + 10 + 3, 90	2, 55 + 10 + 3, 85	2, C + 10, Roh + 3, C	6, 80 + 4, 120

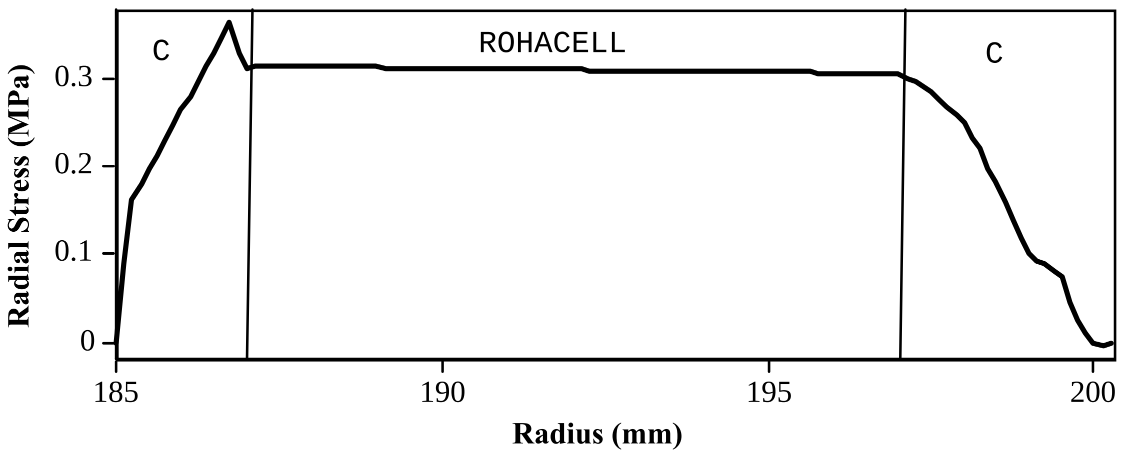

Fig. 13: Calculated residual radial stress vs. radius for sandwich pipe

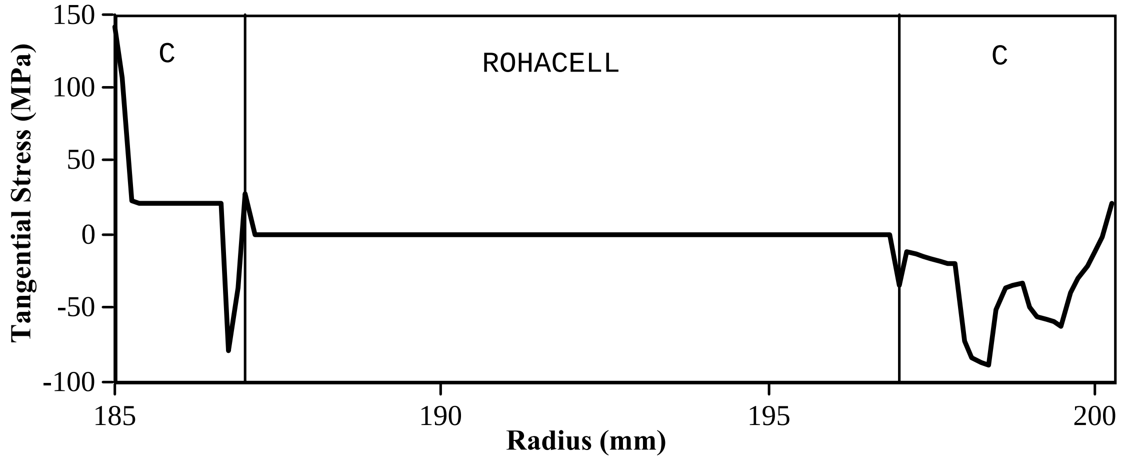

Fig. 14: Calculated residual tangential stress vs. radius for sandwich pipe

CONCLUSIONS

The results indicate that process simulation of multiple material pipe structures can be a useful tool to analyse complex manufacturing processes.

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