EXPERIMENTAL DESIGN APPROACH TO OFF-LINE QUALITY CONTROL IN FILAMENT WINDING

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SUMMARY: Wet filament winding is a common composite manufacturing process for quasi-axisymmetrical components. Thanks to CAD and CIM developments, wet winding has evolved towards an advanced level with respect to design and automation capabilities. However, from a technological point of view, quality control in filament winding remains rather poor. Within the framework of a Brite/Euram project, this quality problem has been dealt with in an experimental way. Large statistically designed experiments have been performed at different partners' sites to create a data bank. These data have been analysed to find new, functional mechanisms. Parameters identified as being significant have been integrated in a mathematical model. This model can be used to select the best material, process and design parameter levels as to optimise the performance of filament wound components. Througout the experiments, several high quality tubes have been wound, with reproducible quasi-zero void content. In this paper the general approach followed in the project is described and the subsequent phases of experimentation are discussed, together with their most relevant results.

KEYWORDS: filament winding, quality control, design of experiments, process optimisation

INTRODUCTION

Wet filament winding is a common composite manufacturing process for tubelike and quasi-axisymmetrical components.

Thanks to CAD and CIM developments, wet winding has evolved towards an advanced level with respect to design and automation capabilities [1] [2] [3], at least with respect to design and realisation of the winding patterns and hence reinforcement configuration.

Although in principle stiffness and strength are accounted for by the fibres, the overall performance of filament wound components strongly depends on the matrix and the fibre/matrix interface. For wound laminates however, data on these material properties are hard to find in literature or supplier brochures. Yet, they are necessary for proper component design and analysis.

In filament winding, matrix and fibre/matrix interface related properties strongly depend on processing conditions. Unfortunately, from this technological point of view, quality control in filament winding is rather poor, in spite of several interesting and promising studies [4] [5]. This as opposed to thermoplastic winding where appropriate processing windows can be found easier [6].

Wet filament winding involves many particular parameters like doctor blade gap, fibre tension, fibre speed, winding angle, etc., which must be set at an appropriate level. Their effect on final product quality is often supposed but not yet uniquely determined. Besides, inherent to the process and its industrial environment, there are also disturbing effects which can not or only hardly be kept under control. Consequently, filament wound products often suffer from significant quality variations, leading to high reject rates, little flexibility for short term diversification, and long expensive start ups of new products.

Within the framework of the Brite/Euram project *FWORM* (BE-5472), this quality problem has been dealt with in an experimental way. Large statistically designed experiments have been performed at different partners' sites to create a data bank. These data have been analysed to find new, functional mechanisms. Parameters identified as being significant have been integrated into a mathematical model. This model can be used to select the best material, process and design parameter levels as to optimise the performance of filament wound components.

This paper describes the general approach followed in the project and discusses the subsequent phases of experimentation with their most relevant results. Because of confidentiality reasons, results are only discussed qualitatively.

EXPERIMENTAL DESIGN APPROACH IN 2 TIMES 4 PHASES

To optimise the filament winding process, Taguchi's approach to experimental design and analysis [7] has been followed, including designing, running and analysing experiments towards off-line quality control and robustness. Taguchi's orthogonal arrays are well known for their efficiency and allow to gain a maximum of information from a minimum amount of experimentation. They have been used to organise the main or basic experiments for model development and the additional experiments for model generalisation.

Split fibre treatment

First, from all partners, the knowledge on the winding process and the back-ground insight in which parameters probably affecting what quality characteristics have been gathered. This revealed that glass and carbon, both fibres envisaged by the consortium, were supposed to behave differently. Hence it was decided to treat them separately, in split experiments (2 times…).

Phases-I and II: basic model development

Based on partners' experience, a limited list of input and output parameters has been composed, valid for both glass and carbon, to be investigated in the basic experiments (phase-

I and -II). The 19 input parameters have been classified in 4 groups: parameters related to the matrix, the reinforcement, process parameters and design parameters. For each input parameter, 2 levels of interest have been considered. The 19 parameters have been organised into a L32 orthogonal array. Because of their simplicity and wide-spread use, tubes were the obvious test specimen.

From the many potential tube quality characteristics, 10 have been retained among which fibre volume fraction (FVF), voidage and interlaminar shear strength (ILSS) are the most important ones. These are all properties which do not directly depend on pure material characteristics but are rather affected by process conditions. Hence, typical mechanical properties like in-plane strength and stiffness have not been considered since they are dominated by the fibre reinforcement. To measure ILSS, standard ASTM-procedures have been adapted as to comply with the curved specimens, cut from the various tubes.

The basic experiments for both glass and carbon fibre have been run at 2 partners' sites. With their individual phase-II results, corresponding tube quality models have been developed for carbon and glass.

Phase-III: model confirmation generalisation

Both models, each based on experimental results from 2 partners, have been confirmed by means of some confirmation runs, and generalised in a third phase by the third production partner, by means of L16 experiments with less parameters and similar but different fibres.

Phase-IV: model validation

Finally, both models have been validated by using them for prototype optimisation. Both carbon and glass prototyping have constituted phase-IV in the experimentation.

Two-stage approach: phases-I and -II

Following this straightforward approach, only one main or basic experiment (common for carbon and glass) would have to be designed including the 19 input parameters and some of their possible interactions, and then tube manufacturing and subsequent quality evaluation would allow to link input parameters to final product quality.

However, the basic experiments have been split up in two stages. A first, machine-dependent stage (phase-I), linking fibre, resin and process parameters to impregnated tow quality; and a second, machine-independent stage (phase-II), linking tow quality together with design parameters and some remaining process parameters to final product (i.e. tube) quality.

Major reasons for splitting the basic experiments in 2 stages are the ability to compare experimental results between specimen production partners with their individual equipment, and the potential to generalise the project results. If experimental data are available on both stages, a 2-stage model can be developed which also third parties (e.g. SME's) could adopt. Only a limited tow experiment would then be required to adjust the first-stage model part to their particular equipment. Figure 1 (full (thin and thick) arrows only) shows the two-stage approach with input and output parameters.

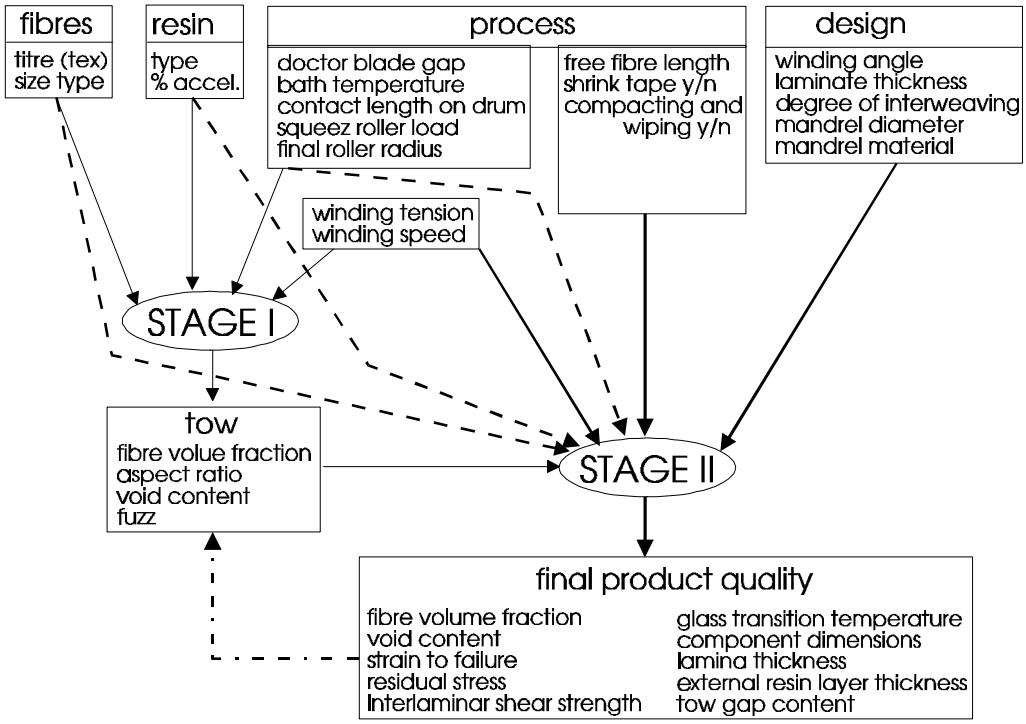

Figure 1: Two-stage approach to filament winding quality control

However, after finishing stage-I, it became clear that it would be impossible to set all stage-II input levels independent of each other, i.e. to realise all desired combinations of tow quality levels independently, with the controllable input parameters of stage-I. Therefore a revised approach has been followed (figure 1, thick (full and interrupted) arrows only). Stage-II would then involve the same input parameters as stage-I, combined with the additional design parameters, and their effect on final product quality would be directly investigated. Based on the tow model (stage-I) and a tube model, it would be possible to reconstruct the link between tow and tube quality, and hence to develop the stage-II model.

DISCUSSION ON STAGE-I: QUALITY CONTROL OF IMPREGNATED TOWS

Figure 2 gives a schematic representation of the winding equipment together with the included input parameters for stage-I. Tow quality characteristics considered can be found in figure 1. The input parameters have been organised into a L32 orthogonal array, allowing to investigate the 11 input parameters at 2 levels each, and (31-11), i.e. 20 of their interactions, with only 32 experiments. 32 tow winding experiments were run with parameter settings as specified in the L32 matrix, and for each run, samples were taken by interrupting the winding, shock-curing and cutting the tows to length.

Carbon results have indicated that for a given material selection, the FVF of the tow can most easily be varied by means of the doctor blade gap, the temperature of the resin bath and the amount of accelerator added. However, carbon fibres with different tex or size exhibit an other impregnation behaviour. Finally, the higher the winding (i.e. impregnation) speed, the more resin is taken along. With glass fibre similar effects were found.

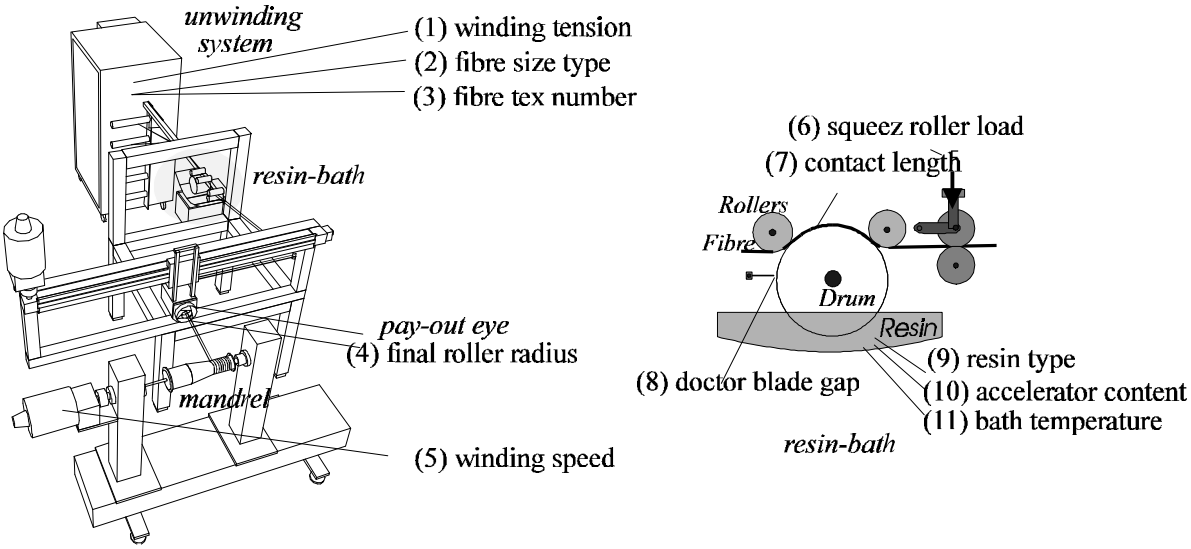

Figure 2: Schematic representation of winding equipment and related input parameters

Low carbon fibre fuzz values (i.e. a measure for fibre damage) in the range of 30 to 100 ppm were obtained by all partners for normal process parameters, indicating a high quality fibre guidance throughout the winding equipments being used. Winding with high tex fibres at low tension was found to create the lowest fuzz, while an appropriate size additionally protects the fibre against damage. Moreover, it was found that the size also plays an important role with respect to voidage. Finally, small accelerator amounts and low resin bath temperatures gave less voids in the tows.

DISCUSSION ON STAGE-II: QUALITY CONTROL OF FILAMENT WOUND TUBES

From all parameters affecting carbon tow FVF, only tex and doctor blade gap, and to a smaller extent also fibre size, seemed to maintain their influence up to the carbon tube level, though with a reduced significance. However, carbon and glass tube FVF seems to be dominated by the winding angle and can be significantly increased by applying a shrink tape, as can be concluded from the halfnormal plot shown in Fig. 3.

ILSS has shown to be very much affected by the size for both carbon and glass fibres. Low tex glass fibres seem to yield better ILSS than high tex fibres. Surprisingly no clear effect of the interweaving of the fibres on ILSS was found. This might be due to the fact that the dimensions of the ILSS specimens were from the same order of magnitude than the tow widths and hence the cross-overs.

Using considerable amount of accelerator yields less residual strains. The likely explanation for this accelerator influence is that increased accelerator content solidifies the tube at lower oven temperature, thus decreasing the temperature difference dependent strains. Because of its higher expansion coefficient, using an Aluminium mandrel yields higher residual stresses than steel.

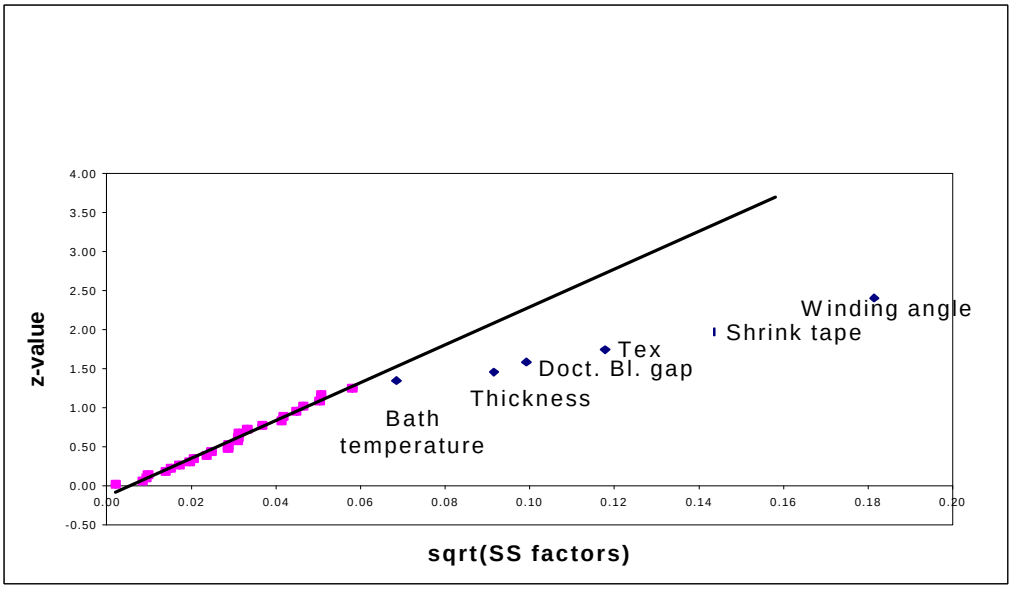

Figure 3: Halfnormal plot showing parameter significances on FVF for carbon tubes.

Glass transition temperature is significantly affected by the amount of accelerator added, i.e. for the epoxy systems used. The more accelerator, the higher the Tg.

With respect to voidage, a clear effect of size for carbon and glass could be traced, which is consistent with the tow results. With carbon fibres, smaller winding angles gave less voids.

From the parameters squeez roller load, contact length on drum, final roller radius and free fibre length, no significant effect was found on none of the considered quality characteristics. In particular for the free length this is a useful outcome because it indicates that continuously varying free length during winding, e.g. to extend winding capabilities in terms of feasible component dimensions and complexities, shorter cycle times…, does not affect final product quality.

The interweaving of the fibres is a dubious parameter. It has been included in the experiments to obtain an objective answer about its influence. In fact, 2 schools exist which both contain part of the truth. On the one hand there is the idea that interweaving *must* lead to stress concentrations and voids, and hence it is recommended to wind as layered as possible [8], [9]. Recently [10] has experienced that with a [± 55°] lay-up, woven tubes have lower tensile strengths, show damage faster and also leak sooner than their layered equivalents. However, no negative effect of interwaeving on voidage was detected. On the other hand several authors mention a positive influence of the interweaving on strength ([11] at [± 64°], [12] at [± 45°]), and, moreover, on stiffness ([13] at [± 25°]). [14] mentions that the torsion strength of thick tubes increases with the degree of interweaving. Finally [15] has shown a positive influence of the winding pattern and hence the degree of interweaving on the buckling load. In between both schools, more moderate conclusions from [16] and [17] can be situated, relativating the effect of interweaving as being of only secondary importance.

However, from all FWORM experiments, no clear consistent effect of the interweaving of the fibres could be derived, at least not for the quality characteristics considered. At first sight it is surprising that fibre cross-overs even do not affect voidage. [10] comes to similar conclusions in his study on the effect of winding patterns and hence levels of interweaving on the amount of porosities in prepreg wound tubes. At none of the FWORM experiments, a negative influence of interweaving on voidage could be detected. Only one partner found for glass fibre a negative influence of interweaving on ILSS. But this was contradicted by other experiments. Hence, it can be concluded that, at least for the not-fibre-dominated material properties, it does not matter whether the actual winding strategy is yes or no interwoven, as long as the positioning accuracy of the fibres is not harmed.

Given both tow and tube models, it should have been possible to reconstruct the link between tow and tube quality, and to distinguish between a machine dependent and machine independent part in the models. Trials have been done, but only with limited success. Yet, for the regression coefficients differing significantly amongst partners, partner-specific correction terms have been added to the quality models.

PHASE-III: MODEL VALIDATION AND GENERALISATION

Some additional carbon and glass tubes have been wound as to confirm both empirical quality models. For carbon, predicted and measured qualities corresponded quantitatively fairly well. With glass, predictions were only confirmed qualitatively.

Both carbon and glass models have been further generalised by means of additional L16 experiments with less input and output parameters, and investigating different fibres.

With respect to the carbon model, an L16 experiment has been run with another type of carbon fibre from the same supplier, but with the size that performed best in phase-II. This explains the extremely low voidages obtained (0.4 % on the average). Overall results were consistent with those observed in phase-II.

To generalise the glass model, an L16 experiment has been run with glass fibre from another supplier. The L16 has been built up, based on an inner/outer array principle. The influence of tex, tension and degree of interweaving, organised in an L4 inner array, has been investigated in several geometrical conditions, represented by an L4 outer array with mandrel diameter, winding angle and laminate thickness as varying parameters. Only the most relevant quality characteristics have been evaluated, i.e. FVF, % voids, FWF and ILSS.

With respect to the influence of the geometrical parameters, quite good correspondence exists with the carbon phase-II conclusions, even better than with glass phase-II results.

Process parameters could only be found back with a limited significance. Nevertheless it was shown that higher tension leads to higher FVF. Besides, small tex fibres are beneficial for ILSS and hence for impregnation quality, which is consistent with the phase-II results. Also a little advantage was seen at small texages with respect to voidage. Hence, it could be concluded that for advanced applications, the higher cost for low tex fibres seems to be justified.

PHASE-IV: MODEL VALIDATION

The generalised glass and carbon quality models have been implemented into a software tool on PC platform.

To validate both quality models, the software has been applied to optimise 2 typical filament winding applications, i.e. a torsion shaft and a pressure vessel.

2 carbon torsion shafts have been wound, one at optimal parameter settings according to the carbon model, and one at a more unlucky parameter combination. Torsion tests on these prototypes have demonstrated the validity of the carbon model.

The glass model has been validated by applying it on a commercial pressure vessel.

From the commercial vessel, the geometry (incl. liner), performance requirements, calculation procedure and resulting laminate lay-up have been simply adopted. This means that for the prototype, the lay-up in terms of helical winding angle, the amount of fibre in the helical layers and in the additional circumferential layers were imposed.

However, the final winding pattern necessary to approximate this lay-up (fibre paths, number of windings pro layer, number of layers, pitches, winding strategy (doi), etc.) as well as the other (sometimes linked) relevant winding parameters (tex, tension, speed,....), has been defined using the FWORM software. These parameters have been set as to optimise the prototype vessel quality towards minimum voidage and maximum impregnation quality (ILSS).

To evaluate this quality, the vessel has been pressurised gradually, with ups and downs, up to twice its design pressure while doing AE measurements to monitor damage. It could be concluded that the design pressure corresponded with a clear but expected onset of matrix damage in the helical layer.

CONCLUSION

To optimise the filament winding process, a Taguchi approach has been followed, including designing, running and analysing experiments towards off-line quality control and robustness.

Experimentation has been organised in 2 times 4 phases. Glass and carbon fibres have been treated separately in independent experiments. For each of both, 4 experimental phases have been worked out.

Stage-I experiments have been run linking input parameters concerning fibre resin and process with tow quality characteristics.

Stage-II experiments have included additional process and design parameters to investigate how tube quality, representative for “final product quality”, is affected. Based on the stage-II results, a tube quality model has been developed for both carbon and glass fibre.

In a third phase, both models have been confirmed through additional confirmation runs and generalised by means of new experiments using other fibres.

Finally, the value of both models has been proved by applying them in the optimisation of 2 prototypes.

Trends derived from all experimentation were similar for the 3 winding equipments on 3 different sites.

Although wet winding is known for its lower quality and poor control on e.g. FVF, the FWORM experiments have shown that, with respect to voidage, wet winding with appropriate parameter settings scores better than dry winding with prepregs. [10] could not reduce the amount of voids in glass/epoxy prepreg tubes below 2 - 2.5 % measured by density and 3 - 4 % measured by means of image analysis. In the wet phase-III experiments however, several quasi porosity free tubes have been wound with glass and carbon fibre and could be reproduced systematically.

ACKNOWLEDGMENTS

The authors thank the European Commission for funding this research project. Moreover, they thank the other FWORM partners, Santa Barbara (E), Urenco (GB), Gaiker (E), Bakelite (D), Tenax fibres (D), IPF (D) and INTA (E), for their collegial and interesting collaboration. The project results were obtained through a laborious but joint effort of all contributing partners.

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