ON THE INVESTIGATION OF RESIDUAL STRESS AND SHAPE DEVIATION DEVELOPMENT IN MANUFACTURING OF GLARE

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Keywords: Fibre Metal Laminates, Manufacture, Distortion, Residual Stresses

Abstract

Integrated fuselage panels made of Fibre metal laminates (FMLs) encounter shape deviations and residual stresses after cure and post-cure processes due to different mechanisms. In this paper, the focus is on the methodology of research that is already started. After describing the manufacturing processes and their effects on the panel geometry and stress state, results from primary modelling and experiments are presented. Some thermal experiments are done on non-symmetric FMLs and remarks are made on the epoxy curing effects. The needed procedure is presented for adapting the model to become capable of predicting the final geometry of a fuselage panel made of FMLs.

1 Introduction

Fibre Metal Laminates (FMLs) are hybrid materials consisting of alternating metal and composite layers. FMLs have found applications in structural parts of aircraft like fuselage panels and leading edges of tail planes. Although, the FML concept is further developed by researchers in the field [1-7], production of integrated panels made of FML has not been analysed and the elastic responses upon manufacturing processes are not yet studied in detail. Investigation of residual stresses and shape deviations induced by manufacturing on the geometry of glass fibre reinforced aluminium laminates (GLARE) and the methodology to reach to a predictive model for that is the main subject of this paper. Manufacturing phases result in deviations from designed dimensions and these inaccuracies hamper the assembly. The residual stresses generated at the same time, reduce the material load capacity of the composite structure made from FMLs and can even cause premature failure.

For many years, efforts are made to model the process of curing during the manufacture of full composite structures [8-13]. Residual stress and distortion occurring in manufacturing can be the result of different mechanisms which can be thermoelastic (reversible) or non-thermoelastic (non-reversible). During cure, polymerization occurs in which by cross-linking, the density of the polymer increases; this causes chemical (cure) shrinkage and the chemical shrinkage induces residual stress. During cool down, thermal shrinkage occurs in the constituents of the material. But, since fibres, matrices and aluminium layers have different Coefficients of Thermal Expansion (CTE) and stiffness E, a cool-down causes laminate distortions from the intended shape and residual stresses. The thermal shrinkage is the most important mechanism in production of FML that produces residual stresses.

Manufacturing processes on FMLs are described and the factors influencing the final geometry and the stress state of the panels are discussed. Research on the prediction and modelling of these effects is in progress and modelling and experimental results obtained up to now are reviewed. In this paper, the focus is on the methodology, i.e. necessary modelling and experimental approaches needed for prediction of the response of the panel during manufacturing. The predictive model will eventually help to revise the mould to produce more accurate integrated panels from glass fibre reinforced aluminium laminates (GLARE).

In the first phase, primary modelling and experiments are performed on FMLs with non-symmetric lay-up of prepreg layers. Thermal stresses and curvature are considered which arise from mismatch of thermal coefficients of expansion of the laminate constituents during cool-down. Selected results are presented from the comparison of curvatures from linear-elastic modelling and experimental measurements. In the second phase, the cure process and effect of different cure stages on the shape deviation of FML is investigated in more detail using the concept of "stress-free temperature (SFT)". Due to cure-dependent properties of prepreg layers and also chemical shrinkage of the polymer, the laminate is free of stress at a temperature different from cure-temperature. Some typical results will be presented and investigations made on the effects from the cure process of FMLs will be discussed.

Further steps needed, i.e. methodology, are presented to obtain a predictive model for residual stresses and distortions in a complete integrated fuselage panel made of FMLs. The full experimental measurements and modelling (simulations) needed are also discussed.

2 Manufacturing procedure and phases

A schematic of the relationship is illustrated in **Figure 1** between different processes that may influence the dimensional accuracy of a fuselage skin panel made of FML. According to **Figure 1**, in most phases, development of residual stress and distortion should be modelled, analysed and measured in order to predict the properties and dimensions of an industrial integrated skin panel.

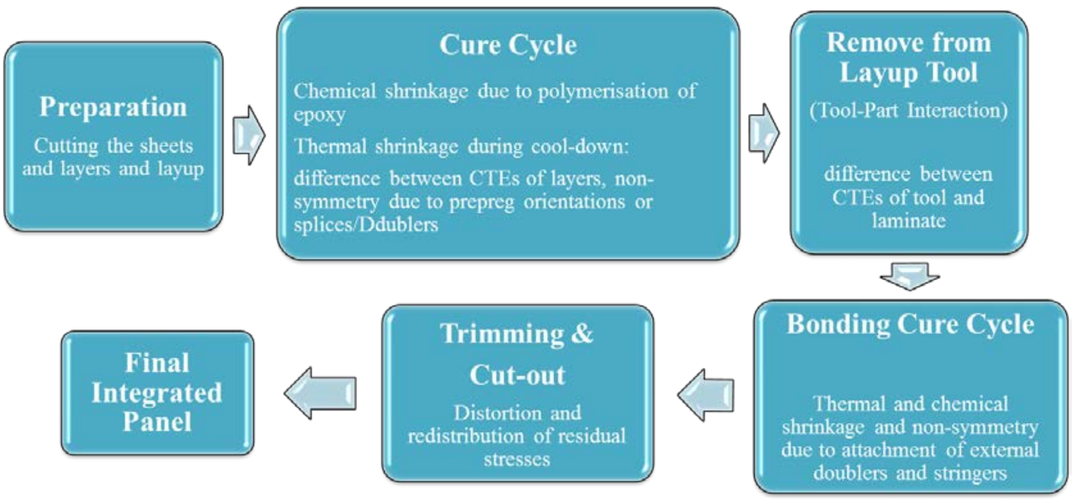

Figure 1: Effect of Different Manufacturing Phases on Residual Stress (Distortion) of FML

3 Modelling development strategy

The ultimate goal of the research, is to have a model to simulate the laminate responses to all manufacturing steps for a complete integrated fuselage panel made of FML. To achieve this, a modelling strategy is used, as shown in **Figure 2**. As the first step, non-symmetrical FMLs are analysed with thermoelastic modelling of cool-down process (model 1). Large displacement nonlinear elastic analysis can be considered for large deflections (model 2). Further improvement of the model accuracy can be obtained by considering cure-dependent material properties and by simulation of the whole cure process including chemical shrinkage. Visco-elastic behaviour of the polymeric epoxy will also be added to the model (model 3). A complete material characterization process needed to include the above mentioned characteristics will be described in the following sections. Furthermore, features like splices, doublers, ply drop-offs and cut-outs are supposed to be investigated that may include some plastic deformation in the aluminium layers (model 4). Post-cure processes [1, 14] for the attachment of stringers and large doublers will be modelled in which viscoelastic behavior of the cured epoxy plays role (model 5). Steps needed for this purpose will be described to be followed later in our research.

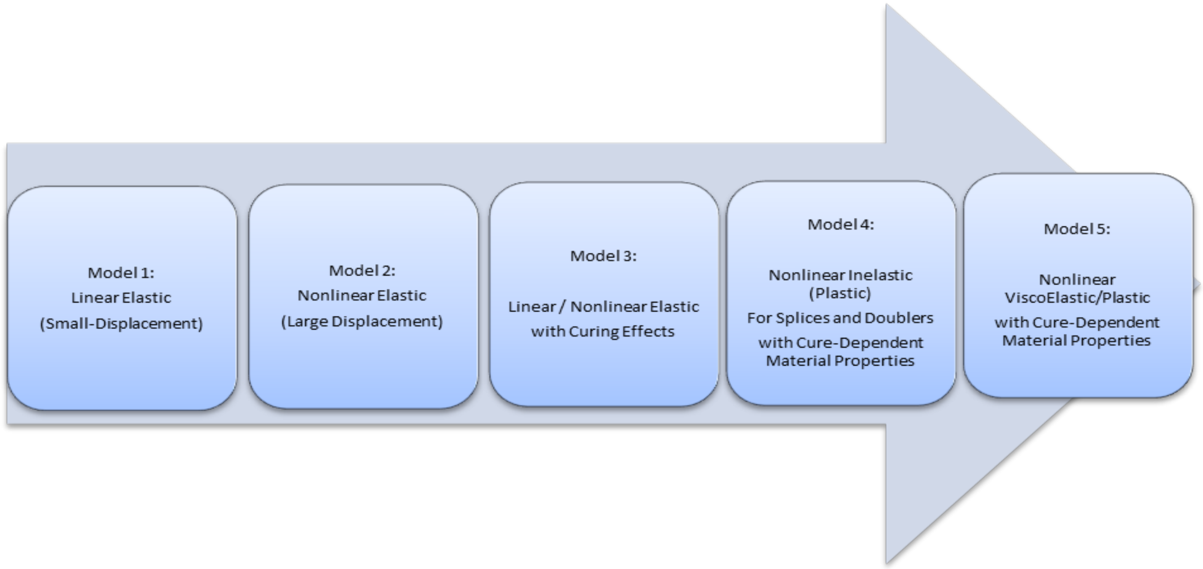

Figure 2: Modelling development

4 Experimental strategy

Experimental investigations and measurements may be used either to validate the model or to identify the important factors for modelling. Measurements are also needed to model the material behaviour.

4.1 Measurement of distortions and residual stresses

Distortions and/or residual strains are measured first for studying the elastic response of different variants of FMLs during manufacturing and second for model verification based upon following approaches:

4.1.1 Approach 1: Direct/indirect measurement on cured samples

The following measurement techniques can be applied on cured FMLs to find the final residual stresses in the laminate:

1- Deflection of a FML beam or strip panel can be measured using methods like digital image correlation (DIC). subsequently, residual strain and stresses can be calculated from cylindrical bending equations.
2- Direct measurement of residual strains of cured laminates can be done using different methods previously applied to full composites and/or metals including:
    - Hole drilling method: mainly for metals that can be used for outer aluminium sheet of FMLs
    - Incremental slitting method: can be used for both metal and prepreg layers of FMLs
    - Layer removal (Peel-ply): a convenient method for measuring strain through the thickness of FMLs

4.1.2 Approach 2: Cure monitoring/measurement during cure:

1- Simultaneous measurement of temperature (using embedded thermocouples) and curvature of panels during cure using DIC or a displacement probe
2- Simultaneous measurement of temperature and residual strains using embedded strain gages or fibre optic sensors

4.2 Material Characterization

For the modelling of the complete cure process as the models aim for, the following measurements of properties would be needed:

4.2.1 Thermal-mechanical properties of the cured material

For improved modelling of cool-down process, change of material properties with respect to temperature should be considered, since the epoxy resin properties of FMLs are dependent on temperature. Change of the coefficient of thermal expansion (CTE) of the epoxy or prepreg layer can be measured using Thermo-Mechanical Analysis (TMA). Glass-transition temperature (T_g) can also be obtained from TMA. The temperature dependent stiffness of the prepreg layer can be measured using Dynamic Mechanical Analysis (DMA). If the measurements are also dependent on time, viscoelastic properties of cured epoxy can be derived from DMA for modelling the behavior of the material's dependency on temperature and time.

4.2.2 Cure kinetics and propertied during cure

Cure kinetics is modelling the completion of cure of a thermosetting resin with respect to applied temperature and time. Differential Scanning Calorimetry (DSC) is used to measure the heat flow into and from the sample during the cure cycle. Onset and completion of cure, degree of cure (DOC) and glass-transition temperature (T_g), all can be obtained from DSC. Furthermore, cure dependent material properties and viscoelastic effects during cure can be derived using DMA during cure of pure epoxy or prepreg.

5 Primary modelling and experiments

In order to have primary understanding of the distortions and residual stresses after cure, a simple thermoelastic model together with manufacturing simple (non-featured) FMLs are used.

5.1 Considering thermal part with non-symmetric layup

Since the cool-down part is dominant in the development of distortions, static simulation of this part of the cure cycle is used as a primary modelling. A similar approach has been used as a first-order approximation on full composites[8, 9]. The thermal load is ΔT, the temperature difference between ambient temperature (T_{amb}=20˚C) and cure temperature (T_c=120˚C). Material properties are assumed to be independent from temperature. Table 1 presents the properties of unidirectional prepreg layers consisting S2-glass fibres and FM94 epoxy (thermoset) matrix and aluminium layers as used in the modelling of GLARE panels and strips. The data are reported in [15] from "Structural Laminates Industries[16]".

S2-Glass/FM94 prepreg					
E_1 [GPa]	E_2=E_3 [GPa]	G_{12}=G_{13} [GPa]	ν_{12}=ν_{13}	α_1[1/˚C]	α_2[1/˚C]
54	9.4	5.5	0.33	6.15×10^{-6}	26.2×10^{-6}
Aluminium 2024-T3					
E [GPa]		*G [GPa]*	ν	α[1/˚C]	
72.4		27.6	0.33	22×10^{-6}	

Table 1: Material properties for GLARE constituents [15]

5.2 Measurement of curvature

A 27×2.3cm strip panel is manufactured with non-symmetric layup (Al-0/0/0-Al-90/90/90-Al). the distortion (curvature) of the panel is measured using Digital Image Correlation (DIC) which gives a complete three dimensional surface of the deformed panel. The comparison of the model results versus measurements can be seen in **Table 2**. The error of -7.5% in model prediction for panel 2 is still useful at least for small rectangular specimens and can be used in the mould correction to decrease the final shape deviation by a considerable amount. Detail description of the modelling and measurements with more samples and discussions can be found in [17].

Mid-span deflection (mm)		Model	Measurement	Error (%)
Panel 1	Al-0/0-Al-90/90-Al	8.46mm	8.49mm	-0.35
Panel 2	Al-0/0/0-Al-90/90/90-Al	9.95mm	10.76mm	-7.5

Table 2: Comparison of the predicted deflection with experimental measurements

5.3 Studying the model accuracy and ways to improve

It can be seen that when the number of prepreg layers per composite layer is increased, the modelling accuracy decreases. The following model improvements are needed for prediction of distortions and residual stresses in FMLs:

- Only thermal shrinkage of the cool-down process from cure temperature to ambient temperature is modelled; chemical shrinkage effects should be added.
- Development of distortion during cure with cure-temperature dependent material properties should be added the model: dependency of the laminate properties on the degree of cure, temperature and viscoelasticity of the epoxy should be considered.

6 Investigation of cure process

After analysing the distortions under temperature gradient (cool-down), study is carried out on the effects of the epoxy cure (before cool-down) on the distortion of FMLs. Here, the experimental study is described and further needed investigations are mentioned.

6.1 Experimental measurement of stress-free temperature (T_{SF})

Here, in order to investigate the cure cycle effects, panels that have curvatures after cure due to un-symmetry are used. The bending strain needed for flattening the panel is measured using strain gages. The panel is heated up in the oven while measuring the bending strain and temperature of the panel. The temperature at which the panel becomes flat is determined when the bending strain of the panel reaches the flattening strain. Thermal residual stresses arise during cool-down process and induce curvature if any non-symmetry is present in the laminate. Therefore, if all of the curvature (or residual stresses) are due to the thermoelastic source, the curvature should vanish at cure temperature. Becoming flat at any other temperature is a sign of significant contribution of other sources i.e. chemical shrinkage and increase of stiffness of epoxy during cure[18]. For panel 2 (**Table 2**), the stress-free temperature is found to be 101 °C which is lower than T_c=120˚C. The difference between $T_{S.F.}$ and T_c shows that after cure and before cool-down, there was a considerable amount of residual stress in the material that was released in a temperature below cure temperature. In a later phase of research, cure (chemical) shrinkage of epoxy in FML should be measured. The curing-induced curvature and strain of the laminate before cool-down should also be determined using a model considering cure shrinkage and increasing stiffness of epoxy.
On the other hand, the glass-transition temperature (T_g) for prepreg layers consisting glass fibres and FM-94 epoxies was measured by M. Hagenbeek in 2005 [15] to be around 67 °C that is less than T_c. Since the epoxy is in its rubbery state during cooling from T_c to T_g, no considerable residual stress is developed in this part[19]. In the next phase of research, dependency of material properties of prepreg layers on temperature will be added to the model. Hereafter, the tasks needed to follow the modelling development strategy (section 3) are described. Experimental strategy (section 4) is used whenever needed.

6.2 Investigating the contribution of different parts of cure on residual stress build-up

As another approach for studying the development of residual stress during cure of FMLs, is to measure the temperature and deflection of the strip panel at the same time. This method will be used in a later phase of the research for determination of residual stresses before and after cool-down.

6.3 Material characterization during cure and cool-down

The phenomena occurring in the epoxy cure cycle should be measured as following:

- Change of CTE and stiffness with temperature using TMA and DMA on cured epoxy/prepreg
- Cure shrinkage of prepreg using dimension change tests
- Cure kinetics of epoxy resin using DSC
- Cure-dependent material properties of prepreg/epoxy using DMA for stiffness moduli (bulk and shear) dependent on temperature, time and degree of cure

7 Effects of making cut-outs in panels made of FMLs

According to **Figure 1**, after cure and removal from mould, the panel is trimmed and cut-outs are made in the FML panel using methods like water-jet and milling (see **Figure 3**). This may increase or re-distribute residual stresses and induce some additional distortions. Simulation with finite element method should be used together with some experimental validation.

Figure 3: A skin panel including cut-outs and reinforcements (doublers and bonded stringers)

8 Effects of adding non-symmetry by splices, doublers and stringers

In the splicing concept, metal layer overlap plus adhesive films are used to overcome the limited width of the metal sheets to make larger panels (**Figure 4**). Splicing has acceptable tolerances and minimum consequences for the local thickness[14]. Skin panels may be flat or single/double curved shells and can be locally reinforced with doublers as additional layers to reduce stress concentrations. Stringers can also be bonded for the same reason and also for increasing the stability of skin panels against buckling (see **Figure 3**). The Splice joints and the reinforcements bring local non-symmetry that produce residual stresses and distortions. The process for manufacturing panels with splices, doublers and/or stringers in 1st or 2nd cure or bonding cycle should also be simulated using finite element method to see the distortions together with experimental measurements.

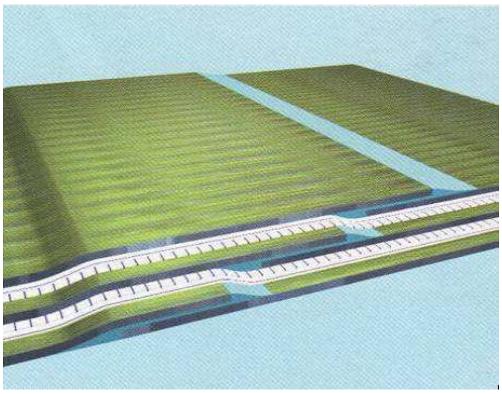

Figure 4: The overlap splice geometry in a GLARE laminate [14]

9 Conclusion

In this paper, the impact of manufacturing processes of FMLs on development of residual stresses and distortions were discussed. The current modelling and preliminary experimental results were presented which were capable of predicting distortions in simple panels with some error. The procedure for improvement of modelling with needed simulations and experimental work were discussed. The methodology described here helps to build a predictive model for residual stresses and distortions in the final fuselage skin panel made of FMLs and for the description of the phenomena occurring during manufacturing.

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