Composite Structures 122 (2015) 546–552

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Investigation of curing effects on distortion of fibre metal laminates

M. Abouhamzeh *, J. Sinke, R. Benedictus

Faculty of Aerospace Engineering, Delft University of Technology, Kluyerweg 1, 2629 HS Delft, The Netherlands

ARTICLE INFO

Article history:
Available online 13 December 2014

Keywords:
GLARE
Fibre metal laminates
Cure process
Bending-strain-free temperature
Distortion
Residual strain

ABSTRACT

In this paper, the curing process of FMLs is investigated as part of a research on modelling the (elastic) response upon manufacturing. The curing process results in shape deviations and residual stresses. In order to build a predictive model, the curing process should be studied with modelling and experiments.

Here, an investigation of the distortion generated in the cure cycle of FMLs is performed which can be used to improve the design of FMLs for fatigue, damage tolerance and residual strength. Non-symmetric panels are made which have a curvature after cure. The determination of the elastic response (distortions and residual stresses) is based on reheating the un-symmetric laminate combined with strain measurement until a balance exists among thermal forces in the layers and the laminate becomes flat (free of bending strain). The so-called bending strain-free temperature deviates significantly from the cure temperature for different panels. This difference is due to the “curing effects” including chemical shrinkage and change of resin properties during cure. A thermoelastic model is developed based on classical laminate theory (CLT) and comparison with the experimental results shows the modelling accuracy and the needed improvements for prediction of the residual stresses and final distortions.

1. Introduction

Fibre metal laminates (FMLs) are hybrid materials consisting of alternating metal and composite layers. FMLs have advantages over other materials like higher residual strength and a better damage tolerance in case of impact, corrosion and fatigue [1,2] which bring enhanced safety and performance to the aircraft industry. Fuselage panels and leading edges of tail planes are among structural parts of aircraft in which FMLs have found applications. Although, the range, understanding and applications of FMLs is further developed by researchers [3–7], the effects of manufacturing processes on the final geometry are not studied in detail yet. As such, the responses of the laminate upon the curing process has not been investigated. Curing process of FMLs, like other full composites based on thermosetting systems, consist of three stages: heating to the cure temperature, curing isothermally and cool-down to ambient temperature. Curing-induced residual stresses have to be considered in design for fatigue resistance and residual strength of FMLs [8–11]. Aluminium panels repaired by composite patches are also hybrid materials in which curing induced residual stresses influence their fatigue life [12,13]. Residual stresses and distortions occurring in laminated parts can be due to different mechanisms which can be of thermoelastic or non-thermoelastic nature. The thermoelastic mechanism that plays a role in the cool-down part of the cure cycle is reversible. However, the non-thermoelastic part is irreversible and occurs in the curing process of the polymer prior to cool-down. The effects from the so called non-thermoelastic mechanisms on the distortion of FMLs during the curing process are here called “curing effects”. The cure process results in deviations from designed dimensions and these inaccuracies hamper the assembly. The residual stresses generated at the same time, limit the material load capacity of the structure made from FMLs. Investigation of the “curing effects” on the geometry and stress state of FMLs is the main subject of this paper.

The most dominant part of distortions in autoclave processing of FMLs is caused by the differences in properties of the laminate constituents. During curing, chemical shrinkage of the matrix occurs by cross-linking due to polymerisation that contributes to the residual stress. During cool down process in composite laminates, contraction or shrinkage occurs in all constituents of the material. Since prepreg layers (consisting of fibres and matrices) and metal layers have different properties specifically directional Coefficient of Thermal Expansion (CTE) and stiffness, residual stresses are produced throughout a cool-down process. If there is a source of un-symmetry, a shape change occurs due to the unbalanced internal forces in the FML.

---

* Corresponding author. Tel.: +31 15 2788673; fax: +31 15 2781151.
E-mail address: m.abouhamzeh@tudelft.nl (M. Abouhamzeh).

http://dx.doi.org/10.1016/j.compstruct.2014.12.019
0263-8223/

Results for full composites are available in the literature for modelling the cure process and prediction of residual stress and distortion [14–19]. After prediction of the distortions, tool compensation can be carried out to manufacture parts from full composites with high accuracy [20,21]. As already mentioned, the most dominant part of distortions are caused by the thermoelastic forces resulting from difference in thermal deformation of constituents during cool-down part of the cure cycle. About the contribution of chemical shrinkage on the final residual stress and distortion, different results are available for different composites. White and Hahn [22–24] state that chemical shrinkage is negligible if the cool-down is not fast. Kelly et Al. [25] found for a resin in an electronic package a response contribution of the chemical shrinkage of up to 70%. Madhukar et Al. [26], Genidy et Al. [27], Russel et Al. [28] and Mergheim et Al. [29] also concluded that chemical shrinkage should be considered in the evaluation of residual stresses. As it can be seen, the contribution of chemical shrinkage is dependent on the specific application, resin type and the cure process. For accurate models in full composites considering chemical shrinkage and cure dependent viscoelastic material properties for the polymer, one can refer to [23,24,29]. It should be noted that other than chemical shrinkage, change of properties of the resin/matrix during cure results in residual stresses in laminates. However, the curing effects are not studied yet for FMLs, so this paper is an investigation on this subject.

The only available literature on FML is the work by Krimbalis et Al. in 2008 [30] who calculated the residual stresses in rectangular symmetric FMLs using simple force-equilibrium equations. Recently, research has been started in the Faculty of Aerospace Engineering at TU Delft (Department of Aerospace Structures and Materials) to study the development of geometric deviations during the manufacture of GLARE. As a first step, geometric responses of square and rectangular GLARE laminates and shells were studied [31,32]. The model was thermoelastic without considering curing effects and considered only thermal cooling from cure to ambient temperature. Such approximation of residual stresses have already been used in the design and analysis of different aspects consisting of fatigue and damage tolerance of FMLs [5,9,10]. In simple thermoelastic models, the laminate is assumed to be free of stress at the cure temperature (beginning of cool-down). However, not always the laminate is free of stress at cure temperature due to the "curing effects" that include: chemical shrinkage of polymer during polymerisation, stress relaxation due to viscoelasticity and variation of properties with temperature change and evolution of cure. In other words, at cure temperature, the laminate may have some amount of residual strain which in non-symmetric panels leads to curvature. Therefore, it is needed also to study the cure process in laminates in order to consider all the mechanisms causing residual stress and distortion. As a result, design of FMLs for fatigue and residual strength can also be improved.

Here, to investigate the curing effects, some panels that have curvatures after cure due to un-symmetry are heated with simultaneous measurement of temperature distribution and mid-panel strain. The temperature at which the panel is free of curvature is called so far in the literature as bending-strain-free temperature but the laminate may not be free of in-plane stresses. Therefore, we will use the term "bending-strain-free temperature (T_{BSF})". A thermoelastic model is developed based on CLT and the deflection and strain of the panels are predicted with and without considering the bending-strain-free temperature (i.e. curing effects). The importance of the effects of cure cycle on the prediction of the residual stresses and distortions of FMLs are discussed and further options for improvements are mentioned.

2. Determination of bending-strain-free temperature (T_{BSF})

2.1. Introduction

Experiments and modelling are used to improve our understanding of curing effects on FMLs. For this purpose, non-symmetric FMLs are manufactured. Thermal residual stresses arise during cool-down and induce curvature if any non-symmetry is present in the laminate. Curved panels are re-heated and the change of curvature with temperature is monitored.

If the entire curvatures (or residual stresses) are due to the thermoelastic source, the curvature should vanish when the laminate is heated to the cure temperature. Becoming flat at any other temperature is an indication of (significant) contributions of other sources, i.e. curing effects. Determination of the bending-strain-free temperature (T_{BSF}) gives an estimate of the accuracy of the model (which is under development) and also would give additional information about the effects from isothermal curing on the final distortion of the laminate.

Here, some related works on full composites are reviewed. Nairn and Zoller in 1985 [33] tested two different unidirectional graphite composites one with an amorphous thermoplastic (polysulfone) matrix and one with an epoxy (BP907) matrix. For the thermoplastic matrix, the residual stresses vanish at glass-transition temperature. They claim that in case of the epoxy matrix composites, the residual stresses start to build up from T_{cure} and do not become zero at T_g but just change direction and may become zero at a temperature ($T_{BSF} = 184\,°C$), which is different from the cure temperature ($T_{cure} = 177\,°C$). For an amorphous thermoplastic matrix, residual stresses build up from T_g during cool-down since above T_g, the elastic modulus decreases dramatically and the thermal expansion coefficient increases. This reduction of modulus above T_g is not that large for highly cross-linked thermoset systems like epoxy.

The initial goal to find the bending-strain-free temperature came from the approach of Castro and Kim in 1993 [34]. They used AS4/3501–6 graphite/epoxy prepreg tapes and heated the curved laminates (due to non-symmetric layup) to a temperature higher than the cure temperature (T_{cure}). The curvature at the bending-strain-free temperature (T_{BSF}) that is higher than T_{cure}, becomes zero. They measured also the glass-transition temperature for different cure temperatures and in all cases, T_g was also higher than the cure temperature. However, as it will be shown in the next section, T_{BSF} for GLARE is below the cure temperature. As another example, residual stress development during cure of an epoxy resin coated on an aluminium film has been observed by Wang et Al. in 1995 [35]. As long as the degree of cure of the epoxy is low, residual stress due to cure shrinkage cannot remain in the material due to rapid stress relaxation. After that (gelation point), the resin will have some amount of residual stress due to the cure (chemical) shrinkage. It was observed that the non-symmetric laminate has some curvature before cool-down (at T_{cure}) in the same direction of the final curvature after cool-down and the corresponding residual strain is designated as ε_{cure} (cure-strain) which is due to curing effects and can be balanced in a T_{BSF} higher than T_{cure}.

The residual strain between T_{cure} and T_{BSF} is due to the curing effects like chemical shrinkage and stiffness evolution of the polymer. On the other hand, the panel in the flat condition is actually free of curvature (bending) strain but in-plane stresses might not be zero. It should be noted that the curvature at the cure temperature due to the curing effects is balanced by the curvature due to thermal loading which can be heating or cooling depending whether the bending-strain-free temperature is higher or lower than T_{cure}. Therefore, using the bending-strain-free temperature