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## EFFECT OF RELEASE AGENT ON PROCESS-INDUCED DEFORMATION IN AUTOCLAVE CURING OF LAMINATE COMPOSITES

Arnon LERDWONGPAISAN<sup>a,b</sup>, Bruno CASTANIE<sup>a</sup>, Philippe OLIVIER<sup>a</sup>

a: Institut Clément Ader, Université de Toulouse, 3 rue Caroline Aigle, Toulouse 31400, France

b: Burapha University, 169 Long Had Bangsaen Rd, Saensuk, Muang, Chon Buri 20131, Thailand

Email: lerdwong@insa-toulouse.fr

**Abstract:** *During manufacturing, composite laminated parts undergo process-induced stresses and frequently exhibit some deformations at the end of cure. Among the different sources inducing these stresses and deformations, our work focusses upon tool/part interaction and more especially on the effects of bagging products. A series of cross-ply and angle-ply laminates were autoclave-cured on aluminium flat mould. Liquid release agent, ETFE release film and peel-ply were placed between the laminates bottom face and the mould. The deflection of all laminates was measured at the end of cure and numerical simulations were performed by FEM (Abaqus) for comparison. These numerical simulations propose an original modelling enabling the behaviour of releasing film and peel-ply to be taken into consideration. It reveals that cross-ply laminates are sensitive to presence of peel-ply layer while angle-ply laminates are less. In this case, the thermal behaviour of releasing film and peel-ply need to be investigated by thermomechanical analysis.*

**Keywords:** Out-of-Plane deflection; Autoclave process; Laminate composite; tool/part interaction

### 1. Introduction

During autoclave curing, composite parts are subjected to the pressure and variation of temperature, residual stress can be generated and the geometric distortion may result due to various parameters [1]. This is a problem in tolerances control especially when the part need to be assembled with other parts, it might have to be forced to fit in and internal stress is built up. Worst-case scenario, those parts can be scrapped.

Several parameters can be considered to be the source of part distortion. These parameters are classically separated into two groups between intrinsic and extrinsic sources. The intrinsic one are related to the characteristic of the part including the original properties of prepreg material, part shape and layup orientation. The extrinsic parameter mainly refers to the manufacturing process including the characteristic of tool/mould and autoclave condition.

The sources of distortion were greatly studied in various literatures and tool/part interaction is the one that is remarkable. Different part geometry and layup directly affect to part deformation. Thicker parts are supposed to have lower distortion compared to thinner part while bigger part is considered to provide larger distortion compared to smaller part. Metallic mould with high coefficient of thermal expansion (CTE) is assumed to induce larger part warpage. The characteristic of mould surface and releasing agent may or may not have an

importance on geometrical distortion. However, the comparison in the midst of research work might be difficult due to various unknown conditions.

Therefore, this work aims to investigate the influence of tool/part interaction to the part deflection. We decided to start from the symmetrical flat laminate with thin layer. The effects of the interface between part and mould surfaces is considered. This work relies on the basis of our previous research [2-5].

## 2. Experimental method

### 2.1 Material and manufacturing

The raw material is a unidirectional prepreg M21EV/IMA provided by Hexcel Composites. 250 x 250 mm cross-ply  $[0^{\circ}_1/90^{\circ}_1]_s$  and angle-ply  $[+45^{\circ}_1/-45^{\circ}_1]_s$  laminates were autoclave-cured using a 2024 aluminium mould. Choosing a 2024 mould with its high CTE enables process-induced deformations to be exacerbated (when compared to the ones that could be obtained with steel or INVAR moulds).

Liquid release agent (Freekote C-600<sup>®</sup>), ETFE releasing film, and peel-ply were placed between the laminates bottom face and the mould. Freekote was applied on the mould surface as a liquid release agent prior placing releasing film and peel-ply. Four different tool/part interfaces were used: 1) Freekote and one layer releasing film, 2) Freekote and one layer peel ply, 3) Freekote and two layers releasing film, 4) Freekote and three layers releasing film. The bagging arrangement is presented in Figure 1. Four samples were provided for each interface configuration, 32 laminate plates were manufactured in total.

The cure cycle consisted in a first isothermal dwell at 150 °C for 1h30 followed by a second isothermal dwell of 1h30 at 180 °C. Heating and cooling rates were set at 1 °C/min. Autoclave pressure was set up to 7 bar (0.7 Mpa).

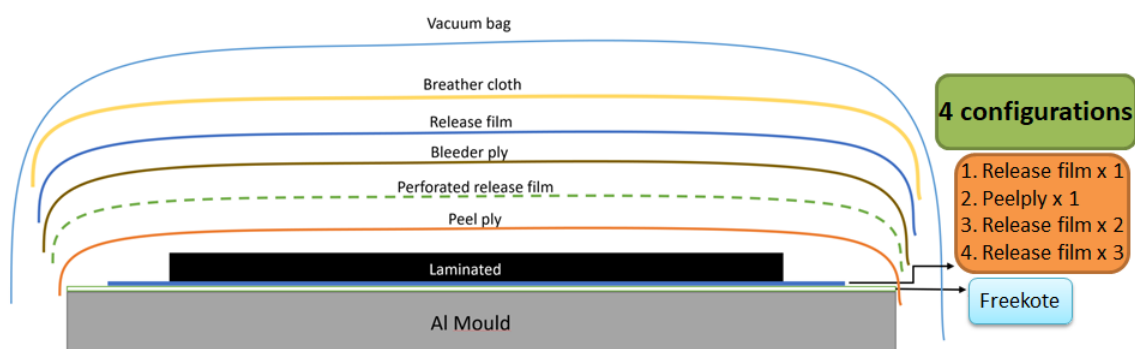
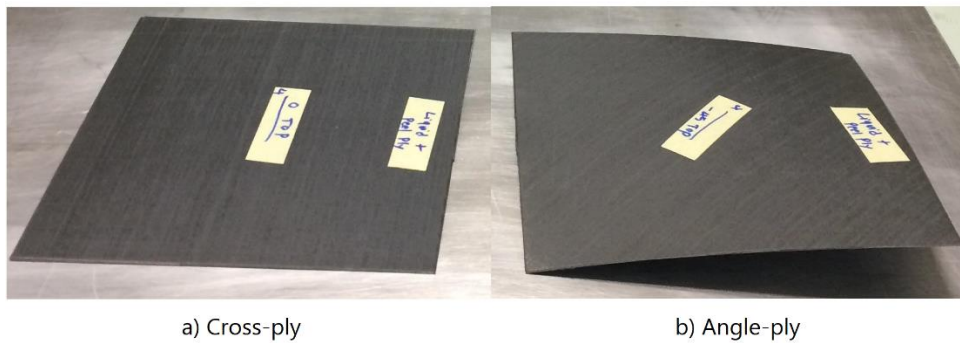


Figure 1. Bagging arrangement for experiment.

### 2.2 Measurement methods

Bagging products were unpacked and all laminates were removed from the mould. There was no difficulty during demoulding due to the existing releasing agent and interfaces. Physical distortion of all specimens was initially observed. The warpage of cross-ply laminate is quite

small and prevalent at the center of the plate while the warpage of angle-ply laminate is large over the whole specimen (see Figure 2).



a) Cross-ply

b) Angle-ply

Figure 2. Specimens distortion pattern.

Two measurement methods, Digital Image Correlation (DIC) and Laser Displacement Sensor (LDS) were employed to determine the magnitude of deformation of all laminates. Technically, the DIC can provide both shape and magnitude of deformation but the LDS was used to ensure the result by measuring the position of maximum distortion size. All laminate plates were spray painted by white and filled with random circular speckle dots on the top surface for DIC image processing. After the DIC measurement was done, the positions of coordinate were provided for 17 measurement points by LDS (see Figure 3). These points are assumed to be able to provide the actual shape of the specimens.

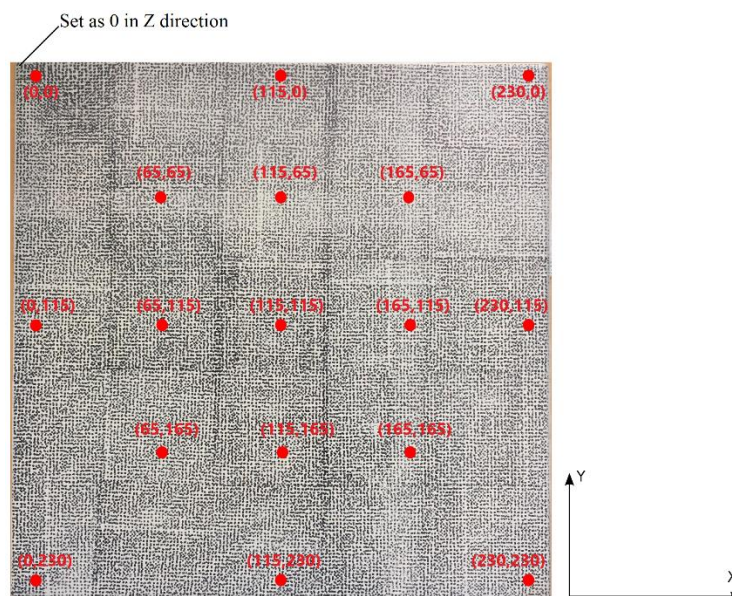


Figure 3. Specimen preparation before measurement and location of the 17 LDS points.

The DIC was operated by two cameras and sufficient light sources installed on the top of laminate in order to capture the specimen's images. Afterward, the magnitude and shape of deformation can be computed by VIC 3D software. For LDS, a semi-automated milling machine was utilised to install the laser head and the use of machine table to change the measuring

positions. Finally, the results from both measurement were compared to ensure the accuracy. The measurement set up for DIC and LDS are showed in Figure 4 a) and b) respectively.

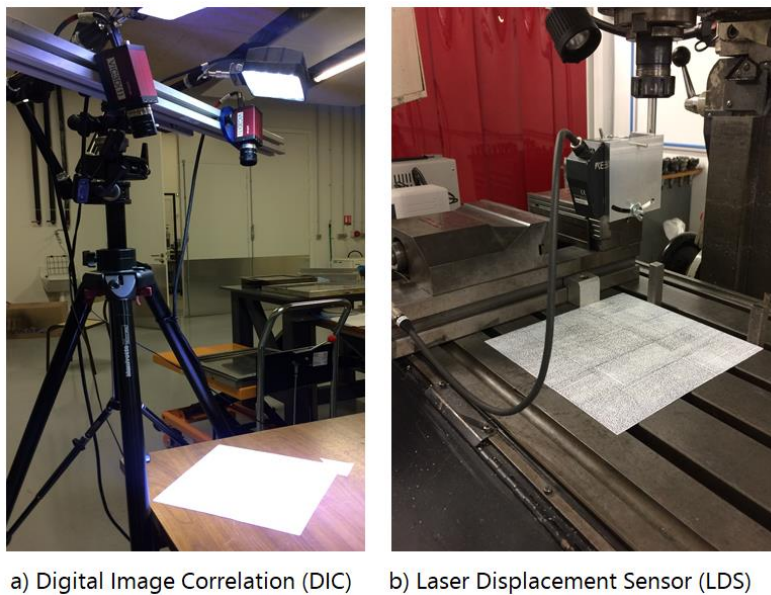


Figure 4. Measurement set up

### 3. Experimental results

DIC provided distortion shape with magnitude in positive and negative values respected to the mid-plane, these two values are summed to gain the total deformation size.

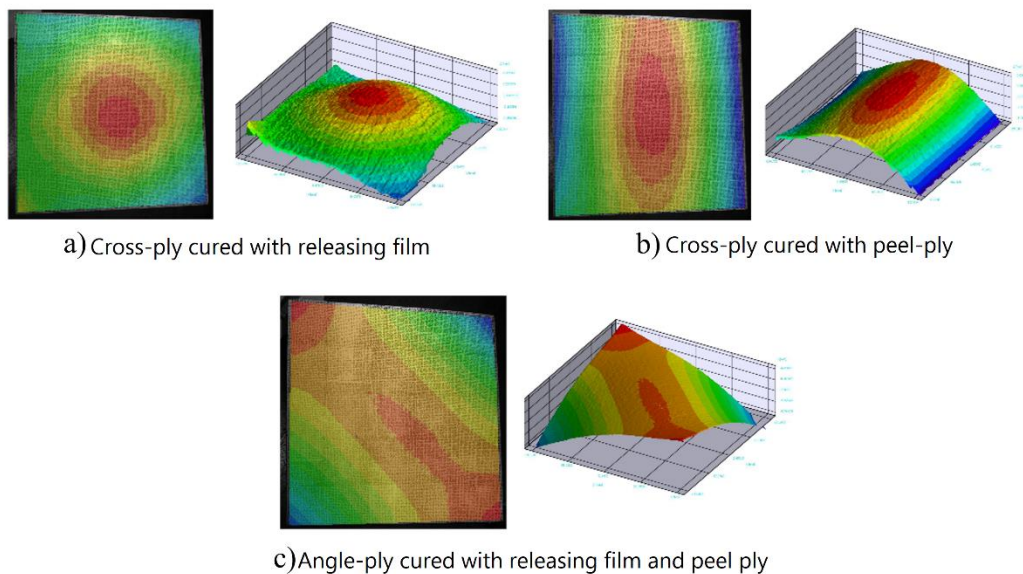


Figure 5. Distortion shape from DIC

This communication only presents the example of distortion pattern for cross-ply and angle-ply laminates cured with releasing film and peel-ply. The different number of releasing film layers has no impact on cross-ply laminate, the distortion pattern is illustrated in Figure 5 a). Out-of-



plane deflections in Figure 5 b) shows that cross-ply laminate is sensitive to presence of peel-ply layer while the deflection of angle-ply laminate does not exhibit any sensitivity to any interfaces presence (see Figure 5 c)). Moreover, The presence of peel-ply increases the magnitude of deformation compared to the use of one, two and three layers of releasing film while no significant difference is observed for angle-ply with various interfaces, these results are indicated in Figure 6. In addition, the maximum distortion valued measured by LDS are consistent with the results from DIC.

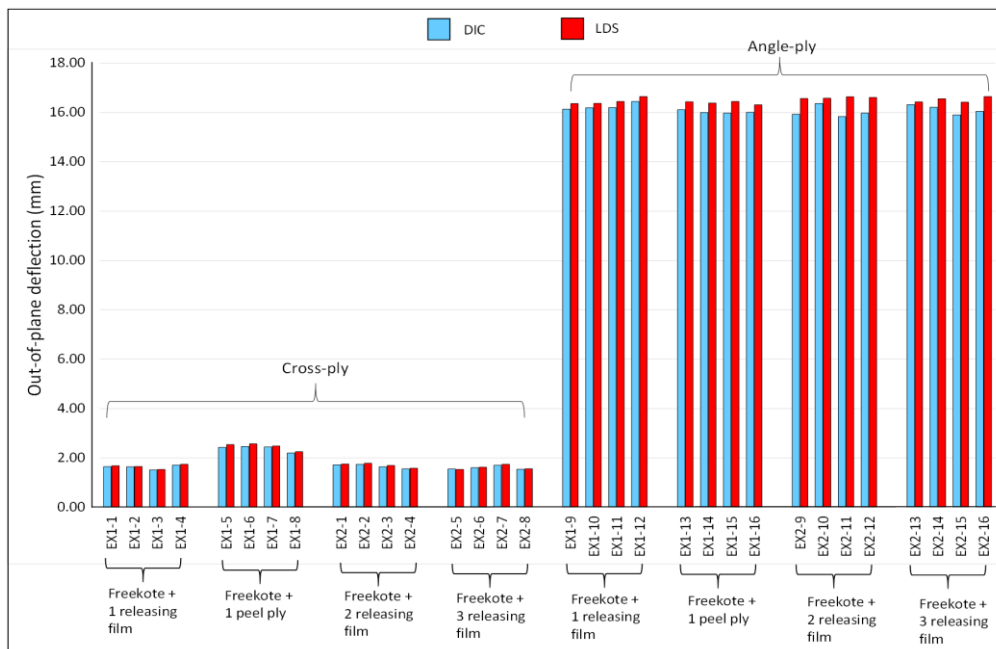


Figure 6. Magnitude of deformation measure from DIC and LDS

#### 4. Numerical Simulation

In order to ensure the accuracy of experimental data, the numerical simulations were performed by FEM (ABAQUS). These numerical simulations propose an original modelling enabling the presence and the behaviour of releasing film and peel-ply to be taken into consideration. Effectively our aim was to improve the multiphysics numerical solution developed previously by the authors [4, 5] to provide a better understanding and modelling of the real influence of releasing agents during curing.

Abaqus 2016 was used to create 3D numerical simulation. The model contains full size of three main 3D solid deformable parts including laminate plate, interface and mould plate (see Figure 7), their properties were collected from many sources [6-12] as presented in Table 1. The thermomechanical model of M21EV/IMA was developed by Moretti et al. and is integrated with this simulation under the form of FORTRAN subroutines, thermo-kinetic, thermo-chemical, chemical shrinkage and thermo-mechanical behaviour were provided please refer to the reference [4, 5].

The simulation consists of three main steps including initial, curing and de-moulding steps. Initial temperature of 20 °C was assigned in initial step while the amplitude of pressure and curing

profile are implemented in curing step, interface and mould is deactivated at de-moulding step to let the laminate to deform at the end of simulation. The model is connected by contact modelling with mesh element type C3D20T standard quadratic with Coupled Temperature-Displacement family.

Table 1 : The properties of aluminum mould and release materials used for simulation

	Density (t/ mm <sup>3</sup> )	Thermal conductivity (T.mm/s <sup>3</sup> ° C)	Young modulus(E) (Mpa)	Poisson ratio	CTE (1/° C)	Specific heat (C <sub>p</sub> ) (mm <sup>2</sup> / s <sup>2</sup> ° C)
Aluminium	2.7x10 <sup>-9</sup>	237	69000	0.346	2.31x10 <sup>-5</sup>	910x10 <sup>6</sup>
ETFE releasing film	1.7x10 <sup>-9</sup>	0.238	800	0.45	9x10 <sup>-5</sup>	1900x10 <sup>6</sup>
Peel-ply	64x10 <sup>-15</sup>	0.28	3550	0.402	9.5x10 <sup>-5</sup>	1670x10 <sup>6</sup>

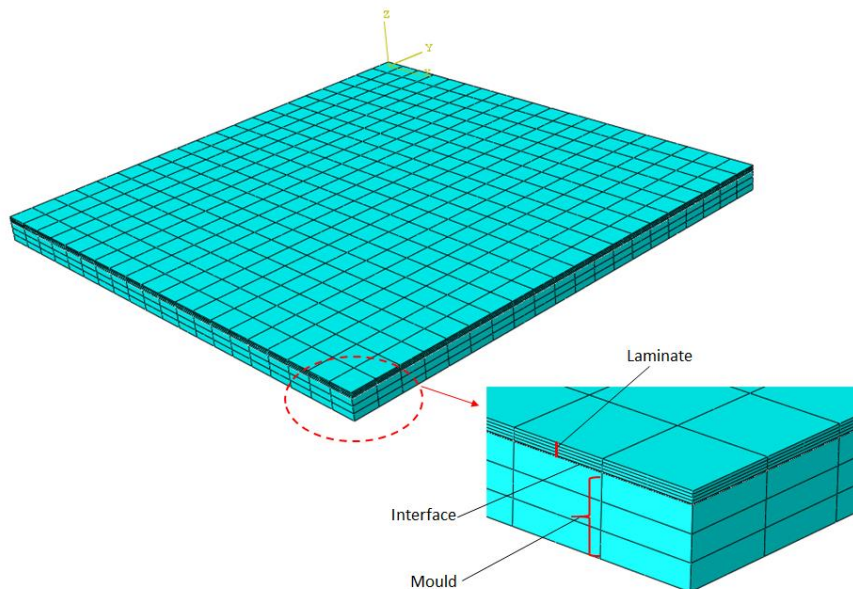


Figure 7. Abaqus model construction

The simulation results are presented in Figure 8. Compare to Figure 5, the agreement between experiment and simulation results is satisfying for both cross-ply and angle-ply laminates, this ensure the efficiency of thermomechanical modelling and curing environment assigned to the model. Simulation results from Figure 8 c) and d) support the experiment in Figure 5 c), it can be concluded that the variation of tool/part interface has no influence on angle-ply laminate. However, the discrepancy between experimental and simulation results is observed for the presence of peel-ply (see Figure 5 b) and Figure 8 b)), further investigation might be required for thermos-mechanical characterisation of textile sheet.

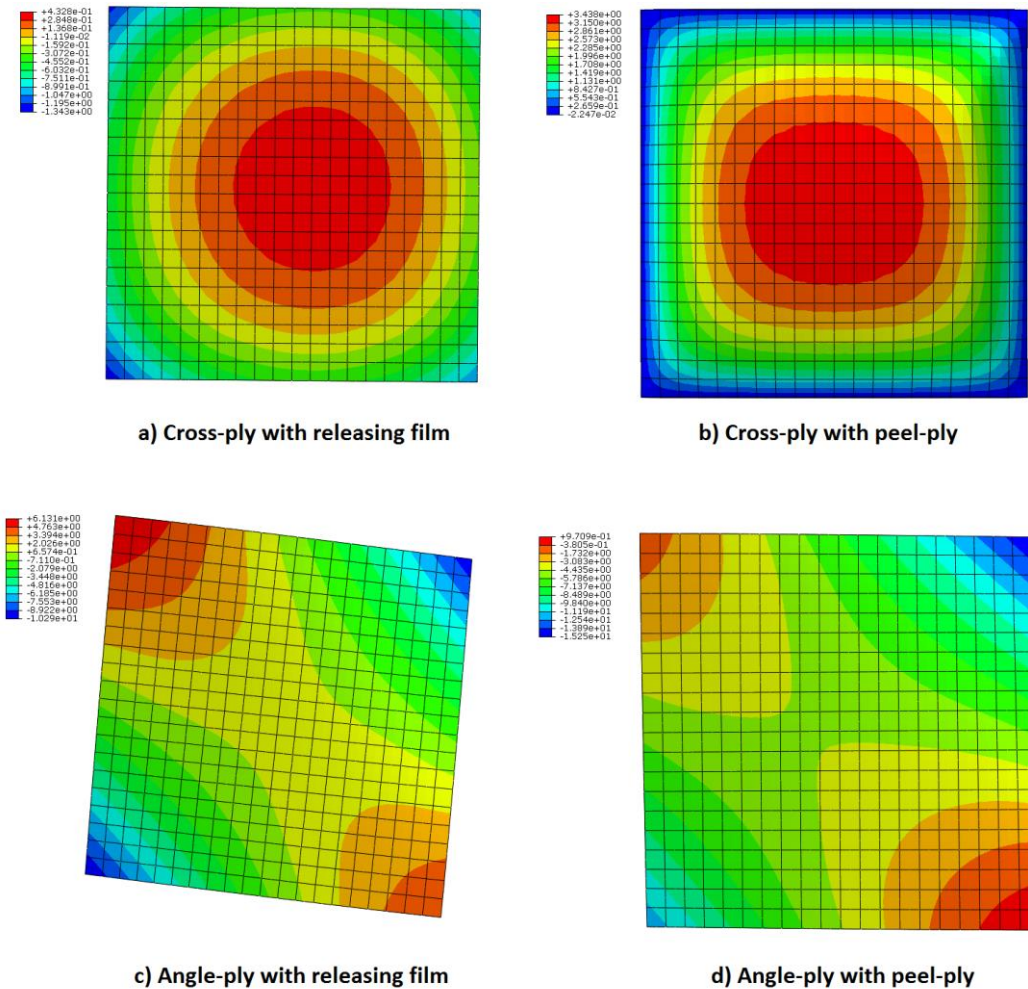


Figure 8. Simulation results

## 5. Conclusion

This study aims to investigate the effect of tool/part interaction to the geometrical distortion of symmetrical flat laminate at the end of cure. The variation of tool/part interface does not play significant role on the distortion of angle-ply laminate while cross-ply laminate is sensitive to the presence of peel-ply and the number of releasing film has no any effect on their distortion so only one layer of releasing film is suitable.

The numerical simulation that employed thermomechanical modelling integrated with tool/part interaction assigned to the model is consistent with the experimental result. However, further studies are required for the modelling of interface materials in order to improve the numerical result.



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