ANALYSIS OF PROCESS INDUCED SHAPE DEFORMATIONS AND RESIDUAL STRESSES IN COMPOSITE PARTS DURING CURE

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Dedicated to loving memory of my grandfather.

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ABBREVIATIONS

DOC	Degree of Cure
CTE	Coefficient of Thermal Expansion
Tg:	Glass Transition Temperature
DSC	Differential Scanning Calorimeter
ACCS	ANSYS Composite Cure Simulation
CLT	Classical Laminate Theory

ABSTRACT

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Process induced dimensional changes in composite parts has been the topic of interest for many researchers. The residual stresses that are induced in composite laminates during curing process while the laminate is in contact with the process tool often lead to dimensional variations such as spring-in of angles and warpage of flat panels. The traditional trial-and-error approach can work for simple geometries, but composite parts with complex shapes require more sophisticated models. When composite laminates are subjected to thermal stresses, such as the heating and cooling processes during curing, they can become distorted as the in-plane and the through-thickness coefficients of thermal expansion are different, as well as chemical shrinkage of the resin, usually cause spring-in. Deformed components can cause problems during assembly, which significantly increases production costs and affects performance. This thesis focuses on predicting these shape deformations using software simulation of composite manufacturing and curing. Various factors such as resin shrinkage, degrees of cure, difference between through thickness coefficient of thermal expansion of the composite laminate are taken into the consideration. A cure kinetic model is presented which illustrates the matrix behavior during cure. The results obtained using the software then were compared with the experimental values of spring-in from the available literature. The accuracy of ACCS package was validated in this study. Analyzing the effects of various parameters of it was estimated that 3D part simulation is an effective and cost and time saving method to predict final shape of the composite part.

1. INTRODUCTION

1.1 Motivation and Scope

The necessity of lightweight design in aerospace and motorsports industry has increased the demand of carbon fiber reinforced plastics composite materials. Over the years composite material manufacturing has been growing progressively. Currently, manufacturing induced deformations are still a challenge for the manufacturers, as those unwanted distortions from the nominal shape lead to increased scrap rates and/or additional difficulties within the assembly process. A connection of deformed parts can lead to a massive increase of the part's internal residual stress level which deteriorate the part's performance.

For small composite parts process induced distortions are not as critical as they are for the larger and complex composite parts. Presently, tool designers rely on their own experience to account for process-induced deformations, often applying a trial-and-error approach to the problem. While this can give reasonably decent results for parts with comparatively modest geometry, composite parts with complex shapes require sophisticated models to capture the interactions between different geometrical features. The most common problem found, using a standard factor of approximation, is that the spring-in varies due to various parameters. Therefore, standard approximation may not be an effective technique every time.

The need of having a reliable approach for predicting these process induced shape distortions has driven researchers to develop new methods. As composite materials are anisotropic in nature, the study of directional properties becomes important while predicting the final material properties. The fiber and matrix behavior during the manufacturing needs a focused study for predicting the final shape of any composite laminate. Analysis of the composite curing process is essential for obtaining the accurate results for predicting the final shape of the composite part. Many analytical methods already exist for calculating the final material properties of the composite materials. Using Classical Laminate Theory (CLT) through thickness coefficient of thermal expansion can be obtained. Different analytical expressions have been proposed previously to estimate the dimensional changes in the laminate. However, using the same expressions may not work every time as those expressions are developed based on a generalized approximation of the various factors affecting the shape distortions. Simulating the entire curing process can be an effective method for predicting the final shape of the composite part. Software results help estimating a more accurate final shape of the composite part which can be used later to compensate during tool design.

1.2 Residual Stresses

Residual stresses that are unavoidably generated in composites while manufacturing, subsequently distort the cured parts to account for these residual stresses. These stresses get built up on fiber-matrix, lamina-laminate, and structural levels. Generation of residual stresses can be attributed to several mechanisms. Inherent anisotropy of composite materials being the prominent one. The coefficient of thermal expansion (CTE) is different in different directions for composite materials. Previous experimental studies show that the coefficient of thermal expansion in resin-dominated directions is much higher than in fiber-dominated directions. The dimensional instability caused due to this difference results in generation of residual stresses. The contraction of any unidirectional ply in transverse direction and through-thickness direction is more than in the longitudinal direction. When cooled, residual stresses are generated in the part which are balanced by the tool when the part is in contact with the tool. The part gets distorted to its equilibrium state to balance the internal residual stresses when the tool is removed.

Resin cure shrinkage is equally significant in generation of residual stresses. For polymeric composites, the resin shrinks when polymerization takes place causing a volume change. Shrinkage is more evident in resin dominated directions of the material. When the resin is heated during cure the resin undergoes cross-linking reactions that lead to an increase of material density and reduction in volume. The two main notable transitions during the curing process of a thermosetting resin are Gelation and Vitrification. Gelation is the process of formation of a 3-D infinite network of polymer chains which is an irreversible process. Vitrification occurs once the glass transition temperature reaches the curing temperature and the resin transforms from the rubbery to the glassy, solid state. The induced stresses which develop throughout cure due to CTE mismatch and resin shrinkage are capable of causing distortion and premature cracking of the composite laminates.

Cure shrinkage effect is a combined effect of cure volume change, resin flow and compaction. The residual stresses at the micro-mechanical level (fiber-resin) as well as at the macro-mechanical level (lamina-laminate) are generated due to cure shrinkage effects. Residual stresses at the fiber-matrix level are often not considered explicitly in the design of composites; frequently they are absorbed as hidden knock-down factors on the strength properties of the material. However, they can generate microcracks and delamination in composites. Residual stresses on the lamina-laminate and structural levels are often calculated using laminate plate theory or finite element analysis. Residual stresses at lamina-laminate level are responsible for part distortion. Intrinsic sources generate residual stress at the constituent level and the effect is integrated up through the length's scales. Extrinsic sources are responsible for generation of stresses at the boundaries of the structure and the effect is migrated down through the length's scales. It is seen that intrinsic sources have the major effect on fiber-matrix level stresses while extrinsic sources have severe effect on the structural level stresses. Reduction in strength and shape distortions are the prime effects of residual stress. Strength of the component is affected by stresses at the fiber-matrix, lamina-laminate and structural levels, whereas dimensional fidelity is affected by only lamina-laminate and structural level stresses to any significant degree.

Another factor that is responsible for generation of residual stresses is tool-part interaction. Due to the difference in CTE of the tool and the ply in contact with tool, the tool and the ply expand at different rate upon heating. This mismatch in expansion is responsible for the residual stresses induced in outer plies of the composite laminate. The frictional forces on the ply in contact with tool cause uneven distribution of thermal strains across the laminate. Upon tool removal this effect can be observed as a distortion in the final part.

1.3 Spring-in and Warpage

When curved composite laminates are subjected to thermal stresses, such as the heating and cooling processes during curing, they get distorted to negate the residual stresses induced due to the difference between the in-plane and the through-thickness thermal expansion coefficient, as well as chemical shrinkage of the resin. The phenomenon of the enclosed angle of curved sections getting reduced is commonly referred to as "spring-in or spring-back". (Depending upon the direction of angular distortion).

Spring-in usually is defined as the difference between the corner angle of the tool; and the corner angle of the final composite laminate. Spring back is seen in initially curved orthotropic laminates when the radial and circumferential dilatational strains during cure are different. In simpler words, due to the uneven distribution of internal residual stresses in through-thickness and in longitudinal direction the spring-in occurs.

Warpage is the deviation of initially flat laminate from flatness due to internal stresses or strains while processing. While processing a composite part on a tool material having high coefficient of thermal expansion, plies adjacent to the tool-part interface may get stretched, which causes a stress gradient through the thickness that locks in when the part cures. As a result, these parts warp away from the tool after processing. In symmetric and balanced laminates, warpage typically arises because of non-uniform properties through the thickness, such as fiber volume fraction gradients, or thermo-mechanical tool-part interaction. Change in composite dimensions is related to many parameters such as: part angles, thicknesses, lay-ups, flange length, but also tool materials, tool surface or cure cycles. The parameters related to material, lay-up, and part shape are called intrinsic parameters and parameters related to processing and tooling are called as extrinsic parameters. This classification permits sources of residual stresses related to material selection and part design to be segregated from sources that are controlled by processing. For thermoset polymer matrices, thermal volume changes of the matrix and fibers are the material related sources of residual stress, and cure shrinkage of the matrix. The extrinsic sources of residual stresses depend on the particulars of the process and include mechanical tool-part interaction and residual stress build-up due to cure gradients during processing.

Tool dimensions are required to be modified to compensate for process induced distortions. Simulating the composite curing process can help to predict spring-in for composite parts before the first physical prototype is produced, reducing process development costs and increasing product quality. Using simulation, it becomes easier to predict the tooling geometry required to consistently produce high-quality structures within tight dimensional tolerances. Simulation can help predict the shape deformations in complex as well as large shaped composite parts accurately. The thermo-mechanical simulation of the curing process can provide the accurate final material state. Simulation based on a previously developed cure kinetic model can be an effective tool to predict the thermally induced residual stresses. The finite element model then helps in predicting the dimensional changes.

1.4 ANSYS Composite Curing Simulation (ACCS)

Developed by LMAT, a consulting services company based in the United Kingdom, ANSYS Composite Cure Simulation (ACCS) is a reliable simulation platform to support manufacturing and tooling engineers throughout the process design cycle.

ACCS was industrialized in response to the growing market demand. The platform has been broadly authenticated and subsequently used to compensate rib, spar and wing-skin tools across the European aerospace and wind energy industries, where previously re-machining the finished tooling after molding the first part was the only method of achieving parts of sufficiently high tolerance to meet strict aerospace assembly rules.

The ability of providing the accurate thermomechanical simulation for the composite curing process makes ACCS a unique software platform. The thermal module provides the results for all the thermal process parameters such as degree of cure, glass transition temperature, material state etc. Previously, for obtaining the thermal results carrying out experiments was necessary. The thermal results obtained are helpful in reducing the manufacturing time and cost as there is no need of conducting the experiments for obtaining the thermal results.

ACCS structural module provides the accurate results for the final shape of the composite part and the residual stresses present in the part post deformation. The compatibility of the software with various other finite element software makes ACCS unique as carrying out the further structural and dynamic analysis on the composite parts is easily possible using the presented methodology.

1.5 Overview of Thesis

This study is focused on obtaining the software results for the prediction of spring-in and residual stresses in composite parts using ACCS. Various parameters have been taken into consideration and the effects of those parameters on the dimensional changes have been analyzed.

The objectives of this research work are as following:

- To predict the process induced residual stresses in composite angular plates using ANSYS Composite Cure Simulation (ACCS)
- To validate the capabilities of ACCS package

- To investigate the effects of various parameters on the spring-in angle
- To compare the results obtained with the analytical and experimental results previously presented by various researchers
- To validate the methodology used based on the comparative analysis between experimental and software results.

This thesis covers all the objectives mentioned above. Chapter 2 provides detailed information about the previous analytical methods used for predicting the spring-in. In chapter 3 the simulation work flow and the cure kinetic model used for the cure simulation have been presented. Chapter 4 contains of all the software results such as spring-in, residual stresses, degree of cure results. Software results considering various factors such as laminate thickness, flange length, width of the part and cure cycles have been presented. Lastly chapter 5 discloses the conclusions of this research study and the possible future scope for the work.

2. REVIEW OF LITERATURE

Process induced distortions in composite materials has been given a lot of focus by manufacturers. Many studies present different methodologies for predicting the material behavior upon curing. The complexity of this issue has forced researchers to study the major factors such as material properties, chemical and thermal cure shrinkage, resin flow, compaction, degree of cure, glass transition temperatures. Various analytical methods have been presented here. Parameters affecting the shape deformations have been discussed in the following sections.

2.1 Material Properties

A composite material can be defined as a combination of two or more materials that results in better properties than when the individual components are used alone. Therefore, while studying the material properties both fiber and matrix properties need to be taken into consideration. While fiber properties are responsible for the strength in fiber dominated direction, matrix properties have a great impact on the strength in through-thickness direction. Therefore, for analyzing the development of residual stresses, understanding resin behavior is necessary.

2.1.1 Glass Transition Temperature

Curing process consists of series of thermo-chemical reactions where the liquid state resin is converted to rubbery solid first and then to a glassy solid state. The temperature at which gelation occurs is known as the glass transition temperature. Epoxies being the thermosetting materials, during the curing process, the final cured epoxy materials do not melt or reflow when heated but usually get softend at elevated temperatures. Having the exact values of glass transition temperature is important in estimating the material behavior at phase change [1].

2.1.2 Degree of Cure

Degree of cure at specific time can be defined as the ratio of the summation of reaction heat at that specific time to the summation of total heat during the entire cure cycle [2].

$$\alpha = H/(H_T + H_R) \tag{2.1}$$

Where α is the Degree of cure at specific time, H is the summation of reaction heat till specific time from the beginning of the reaction, H_T is the heat of entire cure cycle and H_R is the residual reaction heat.

DOC can be calculated experimentally using a differential scanning calorimeter

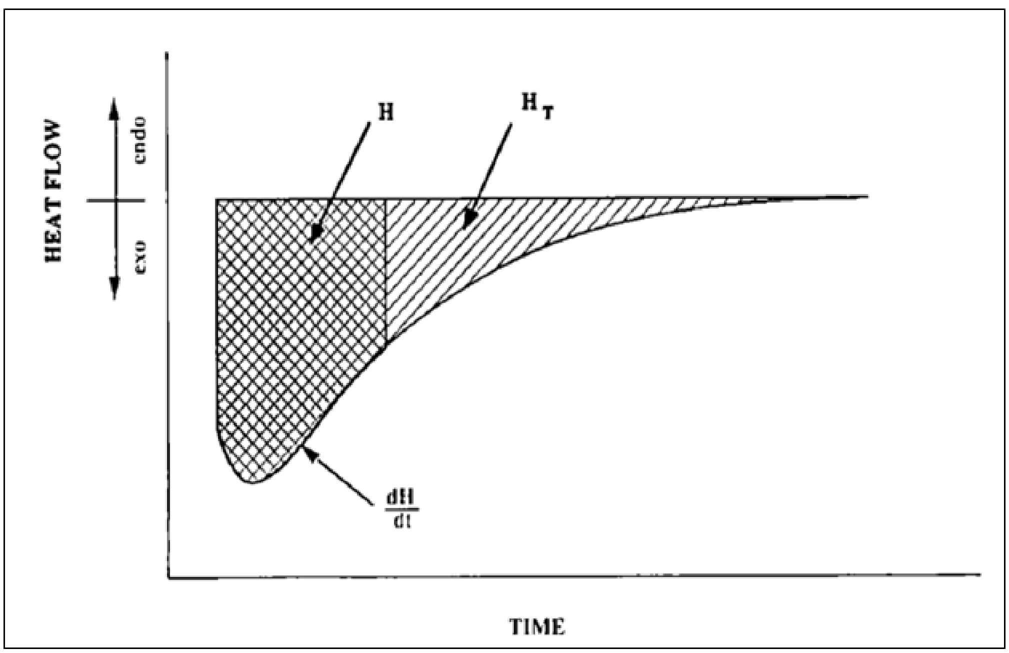

Fig. 2.1.: Heat of reaction response using DSC

(DSC). DSC measures the instant heat of reaction and DOC can be calculated. Figure (2.1) shows a typical DSC response for a single-step cure cycle [3].

Upon providing enough heat flow as activation energy for the chemical reactions the following exothermic reactions take place. There is an increase in rate of DOC at the beginning of the cure. The heat flow is then observed to be decreasing during later stages of curing. Therefore, the heat of reaction is the area under the curve shown in figure 2.1. It can be implied that the relation between the DOC and heat of reaction is nonlinear function of temperature and time-history. Various cure kinetic models provide different relations for the rate of DOC. It can usually be assumed that the rate of DOC is the function of DOC and temperature. [4]

$$d\alpha/dt = f(\alpha, T) \tag{2.2}$$

Where α is degree of cure, T is the temperature and dα/dt is rate of reaction.
The rate of reaction can also be expressed in the form of rate of heat flow is proportional to the rate of the heat flow. It is assumed that the rate of reaction is proportional to the rate heat flow. Hence, rate of reaction is expressed as,

$$d\alpha/dt = 1dH/H_T dT \tag{2.3}$$

Where, H_T is total heat of reaction for the entire cure cycle and dH/dT is the heat flow rate.
Table 2.1 lists few of the cure kinetic models that are being commonly used [3] [5] [6].

Table 2.1.: Cure kinetic models

No.	Model	Equation
1	Springer-Loss	$\mathrm{d}\alpha/dt = (k_1 + k_2\alpha)(1-\alpha)(B-\alpha)$
2	Cole with Diffusion	$\mathrm{d}\alpha/dt = (1/(1+e^{c(\alpha-(\alpha c_0+\alpha_c T))}))K_1\alpha^m(1-\alpha)^n$
3	White and Hanh	$\mathrm{d}\alpha/dt = K_1\alpha^m(1-\alpha)^n$
4	Kamal	$\mathrm{d}\alpha/dt = (K_1 + K_2\alpha^m)(1-\alpha)^n$
5	Kamal with Diffusion	$\mathrm{d}\alpha/dt = (1/(1+e^{c(\alpha-\alpha_c)}))(K_1 + K_2\alpha^m)(1-\alpha)^n$
6	Johnston and Hubert	$\mathrm{d}\alpha/dt = (K\alpha^m(1-\alpha)^n)/(1+e^{c(\alpha-(\alpha c_0+\alpha_c T))})$
7	Lee, Chiu and Lin	$\mathrm{d}\alpha/dt = K_1(1-\alpha)^1 + K_2\alpha^m(1-\alpha)^n$

Table 2.2.: Parameters of cure kinetic model

No.	Parameter	Expression
1	$K_{\mathrm{i}} = Ae^{\Delta E_{\mathrm{i}}/RT}$	Arrhenius factor
2	α	Resin degree of cure
3	ΔE_{i}	Activation Energy
4	R	Universal gas Constant
5	T	Temperature
6	A	Pre-exponential factor
7	m.n	Equation subscripts
8	C	Diffusion constant
9	$\alpha_{\mathrm{C0}}, \alpha_{\mathrm{C}}$	Critical DOC dependent and independent of temperature respectively

The constants of curing kinetic models can be obtained using a mathematical formula fitted with the experimental data using statistical software like MATLAB [4].

2.2 Cure Shrinkage

Volumetric changes are one of the main causes of dimensional variability and residual stress development during the cure of composite materials. The volumetric changes of a thermoset resin are a combination of chemical effects (shrinkage) and thermal effects (CTE) [7]. the Van der Waal bonds between resin molecules convert to shorter bonds during the series of chemical reactions. The polymerization occurred causes a reduction in resin volume which is called cure shrinkage. Cure shrinkage

occurs parallelly with other mechanisms like resin flow and compaction. Therefore, estimating exact value of cure shrinkage is difficult to calculate. A model was developed by Bogetti and Gillespie [6] which described volumetric change in the epoxy resin during curing process. Cure cycle was divided into three regions where resin was assumed to be a viscous fluid in the first stage. The second region was where the maximum shrinkage occurs, and the third region was considered where the curing process is completed where no further shrinkage occurs.
Based on their model volumetric shrinkage can be expressed as,

$$\Delta V_r = \Delta\alpha/(\alpha_{diff}^{shr}).v_{shr}^T \tag{2.4}$$

Where Δv_r and v_{shr}^T are incremental and total volume shrinkage respectively. $\Delta\alpha$ is the incremental change in DOC and α_{diff}^{shr} is the DOC the moment chemical shrinkage ends.

2.3 Coefficient of Thermal Expansion

In previously referred studies, for CTE of uncured composite parts CTE of cured composite parts was used for reducing the complexity. While classical laminate theory can be used to calculate the CTE for composites many researchers have presented micromechanics models to obtain the values of post cure CTE.
For developing a model White and Hahn [3] used strain gauges installed on the surface of the outer layer of the composite. Thermal strains were obtained in both longitudinal and transverse directions during cure. CTE then was calculated using the expressions derived using classical laminate theory.

2.4 Stress Development in Composites

The governing equations of the stress analysis are based on the classical laminated plate theory. A finite element incremental method can then be employed to solve the equations, if the fiber properties are constant or only function of the temperature and the resin behaves as a "cure-hardening instantaneous linear elastic" material. For a given increment, knowing the field of degree-of-cure and temperature from the heat transfer analysis, the instantaneous composite elastic constants can be computed using the resin elastic modulus model and the micromechanics approach. [8] Similarly, the thermal and chemical strains can be calculated for a given increment knowing the resin thermal and shrinkage behavior with the temperature and the DOC and using the micromechanics approach. The stresses in the laminate can be then calculated from the classical laminate theory. Development of residual stresses can also be a function of time. It has been previously presented [3] that mechanical strains applied to the composite early in the cure cycle have a significantly smaller effect than strains applied late in the cycle due to the large difference in the rubbery and glassy modulus. Developed residual stresses lead to the shape distortions upon removal of tool.

2.5 Analytical Calculation of Spring-in

Various studies have provided various analytical methods for predicting the spring-in. While few studies consider the impacts of both CTE and cure shrinkage, few approaches have also considered the effect of moisture. [9] [10] [11]

Spring-in can be defined as the reduction of closed angles due to process-induced stresses or strains. Spring-in generally occurs in curved orthotropic laminates if the radial and circumferential dilatational strains during processing are different i.e. differential residual stresses are generated through the thickness of the composite laminate. Spring-in is usually caused by cylindrically orthotropic strain in the laminate due to cool down from the equal dimension temperature, due to chemical shrinkage of matrix and residual stresses present in the laminate at the full cure temperature. Spring in due to orthotropic dilatational strain is associated to the difference between the out-of-plane (radial) and in-plane (circumferential) strain [12].

Radford proposed a simple equation for predicting spring-in of angled laminates based on material anisotropy [2]. This equation accounts for the temperature difference between cure and ambient conditions, the anisotropy of thermal expansion and cure shrinkage, and the part angle.

$$\Delta\Theta = \Theta(\varepsilon_{\mathrm{l}} - \varepsilon_{\mathrm{t}}/1 + \varepsilon_{\mathrm{t}} = \Delta\Theta_{\mathrm{CTE}} + \Delta\Theta_{\mathrm{CS}} = \Theta((\alpha_{\mathrm{l}} - \varepsilon_{\mathrm{t}})\Delta T/1 + \alpha_{\mathrm{t}}\Delta T) + \Theta(\phi_{\mathrm{l}} - \phi_{\mathrm{t}}/1 + \phi_{\mathrm{t}}) \quad (2.5)$$

where: $\Delta\Theta$= spring-in angle; $\Delta\Theta$ CTE= thermal component of the spring-in angle; $\Delta\Theta CS$= cure shrinkage component of the spring-in angle; α=coefficient of thermal expansion; = resin shrinkage; subscripts l and t refer to the longitudinal and transverse directions respectively.

The thermal component of spring-in arises due to the difference in through- thickness coefficient of thermal expansions for any composite laminate. The expansion in longitudinal direction is different than the expansion in transverse direction due to the material property distinction of fiber and matrix. The thermal component is significant during the cool-down from the final hold temperature [2].

3. PROPOSED APPROACH

In this chapter we are presenting a comprehensive methodology to address the shortcoming of the analytical methods discussed in previous chapters. A cure kinetic model which would explain the curing process is presented here. Also, the simulation workflow has been explained in this chapter.

3.1 Scope

The methods presented in previous chapter provide the analytical expressions to predict the spring-in for angular composite parts. However, effects of various parameters such as laminate thickness, flange length, part width were not considered in those studies. Part geometry is one of the prominent parameters which affects the shape distortions in composites. Here we have presented a methodology which not only takes the effects of CTE and cure shrinkage into consideration but also studies the effects of part geometry. Estimating the dimensional changes using simulation helps in reducing the time required for analysis as well as the cost can be reduced as the manufacturing the prototypes is not required post simulation.

The thermal-mechanically coupled simulation of the composite plate is based on following phenomena that influence the results:

- Thermal Strains in the material
- Material Shrinkage
- Temperature dependent structural properties
- Viscoelastic behavior of the material

The simulation process can be complicated as composite materials are anisotropic. The material properties vary when the resin is converted from a liquid state to a gel state and then to a glassy solid state. Hence predicting the final material state post curing is the most important part of the simulation. Accurately predicting the post cure material properties results in predicting the final shape and accumulation of residual stresses in parts.

As discussed previously, cure shrinkage plays an important role in generation of residual stresses. Resin cure shrinkage in all three directions (X,Y,Z) is considered based on material properties and then applied in predicting the volumetric changes in resin during the thermal curing process. A sophisticated thermo-mechanical model has been presented to accurately predict the part distortions in timely manner.

3.2 Simulation Workflow

ANSYS Composite Cure Simulation (ACCS) was used to analyze the residual stresses and spring in composite parts. The ACCS is fully integrated into the Workbench environment. The composite material data necessary for the cure simulation are stored in the engineering data module. Connectivity to ANSYS Composite PrepPost, as well as other ANSYS products, enables seamless exchange of simulation and process design data. The connection with ANSYS DesignXplorer enables advanced design optimization of material and manufacturing process parameters [13].

The ACCS chemical solver is embedded within the transient thermal module and simulates development of polymerization and glass transition temperature, as well as internal heat generation related to exothermic cross-linking reactions. Subsequently, thermal and cure data is passed into the structural data module where the ACCS cure material model calculates development of residual stresses and process-induced distortions. For relatively thin laminates (¡ 5 mm thick), where a uniform temperature distribution can be assumed, ACCS offers a quick three-step simulation approach. This quick solution can be used in the early design stages for quick assessment of the process parameters. Once the simulation process is completed the distorted geometry of the finite element model can be used to generate compensated tooling geometry.

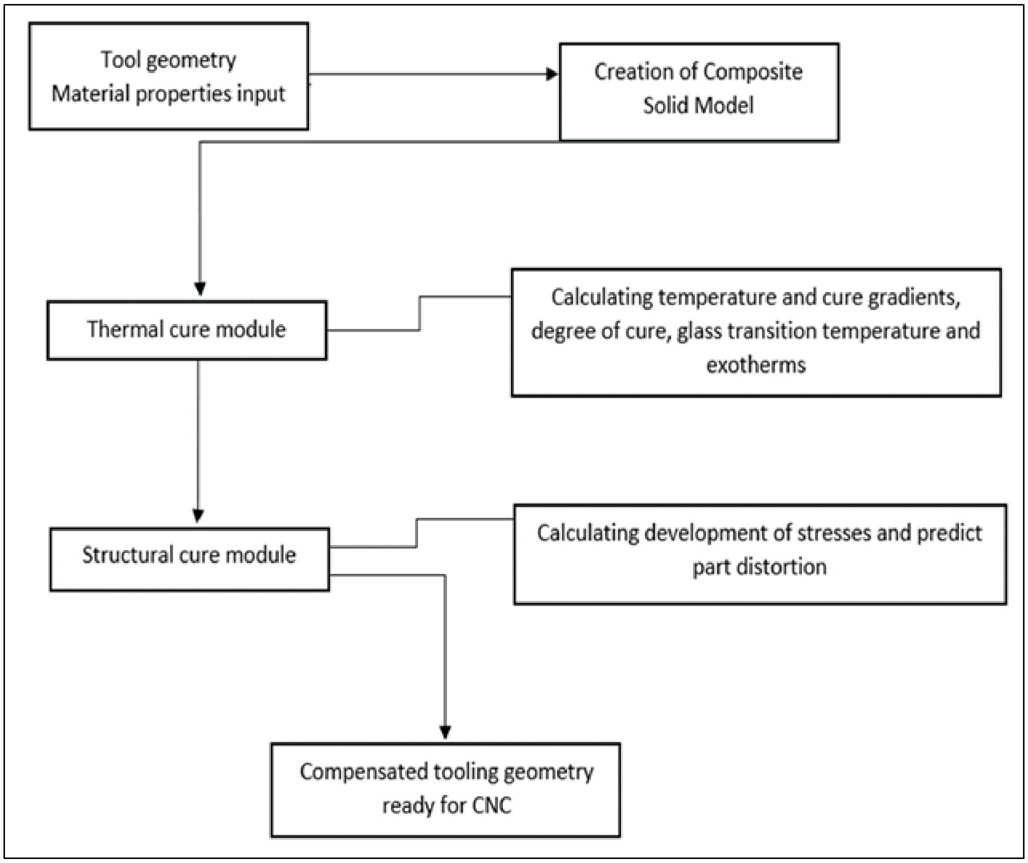

Fig. 3.1.: ACCS simulation workflow

3.3 Cure Kinetic Model

The resin characterization is a key element in the manufacturing of composite materials. Resin processing properties and their associated constitutive models are essential in order to define and optimize the processing parameters and predict the final properties of a composite structure. ACCS uses the exact same cure kinetic model which LMAT have developed and compared with the one presented by Lolei Khoun, Timotei Centea and Pascal Hubert [7]. The simulation results are obtained using the cure kinetic model presented by researchers where the case study on CY-

COM 890RTM Epoxy Resin was conducted to investigate thermomechanical behavior of the resin.

3.3.1 Total Heat of Reaction

The total heat of reaction released during the cure dynamic is usually measured using modulated differential scanning calorimeter (MDSC) , whereas isothermal scans are used to monitor the heat flow during a series of isothermal cures. The measured heat generated by the resin can be then converted into cure rate based on the assumption that the rate of reaction, $d\alpha/dt$, where is degree of cure, is proportional to the rate of the heat flow, dH/dt:

$$\frac{d\alpha}{dt} = \frac{1}{H_{\mathrm{T}}}\frac{dH}{dt} \tag{3.1}$$

where H_{t} is the total exothermic heat of reaction.

Estimation of rate of reaction is important for predicting the material phase and resin characterization.

3.3.2 Degree of Cure

The degree-of-cure of the resin can be obtained by integrating the area under the curve of cure rate vs time [7].

$$\alpha = \frac{1}{H_{\mathrm{T}}}\int_0^t (\frac{dH}{dt})dt \tag{3.2}$$

Fig. 3.2 shows the comparison of the experimental data and predicted autocatalytic cure kinetics model for isothermal tests conducted by Lolei Khoun, Timotei Centea and Pascal Hubert [7]. Thus, the cure rate can be expressed as a function of the degree-of-cure and compared to existing cure kinetics models. The constants of curing kinetic models can be obtained using a mathematical formula fitted with the experimental data using statistical software like MATLAB. The autocatalytic cure model with a diffusion factor developed by Hubert et al. [7], is expressed by the following equation:

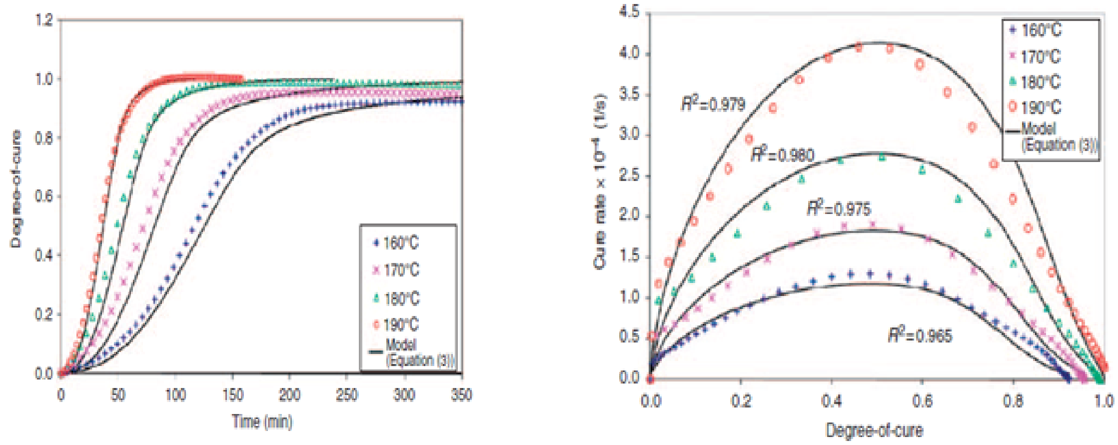

Fig. 3.2.: Comparison of experimental data and predicted autocatalytic cure kinetics model for isothermal tests (a) degree-of-cure with the time, (b) cure rate as a function of the degree-of-cure.

$$\frac{d\alpha}{dt} = K\frac{\alpha^m(1-\alpha)^n}{1+exp[C(\alpha-(\alpha C_{\text{o}}+\alpha CT^T))]} \tag{3.3}$$

where K is a rate constant following an Arrhenius temperature dependency.

$$k = Aexp\frac{-E_{\text{A}}}{RT} \tag{3.4}$$

The autocatalytic model with the following constant values, A=58528 s-1, Ea=68976 J/mol, n=0.6, m=0.63, C=15.66, $\alpha C0$=-0.90 and αCT =0.0039 K-1 accurately predicts the resin cure evolution for the different dynamic and isothermal cases considered [7].

3.3.3 Glass Transition Temperature

The glass transition temperature (Tg) significantly affects the resin mechanical properties as it changes from its rubbery to its glassy state. An increase in the CTE is noticed when the resin progresses from its glassy state to its rubbery state with a temperature ramp. The evolution of the Tg with the degree-of-cure was modeled with the DiBenedetto equation [7].

$$\frac{T_{\mathrm{g}} - T_{\mathrm{g0}}}{T_{\mathrm{g}} - T_{\mathrm{g}\infty = \frac{\lambda\alpha}{1-1-\alpha}(3.5)}}$$

where Tg is the glass transition temperature, $\mathrm{T}_{\mathrm{g}\infty}$ *and* T_{g0}

As previously mentioned, Bogetti and Gillespie model [18] was used to calculate the cure shrinkage during the cure.

$$\Delta v_{\mathrm{r}} = \frac{\Delta\alpha}{\alpha_{diff}^{shr}} v_{shr}^{T} \tag{3.6}$$

Where $\Delta v_{\mathrm{r}}$and v_{shr}^{T} are incremental and total volume shrinkage respectively. $\Delta\alpha$ is the incremental change in DOC and α_{diff}^{shr} is the DOC the moment chemical shrinkage ends.

3.4 Material Properties

Hexcel AS4-8552 was the selected curable material used inside ANSYS. Hexcel AS4-8552 is a unidirectional prepreg with a high-performance tough epoxy matrix. This material is widely used in primary aerospace structures. It exhibits good impact resistance and damage tolerance for a wide range of applications. Hexcel AS4-8552 shows good translation of fiber properties. For simulating the entire curing process, it is necessary to have the all the orthotropic properties available during the analysis. The cure kinetic equations are then used to obtain the results such as DOC, material state, glass transition temperature and heat of reaction. Following table illustrates all the material properties associated with Hexcel AS4-8552. The material properties presented in the following table were pre-defined inside ANSYS. It is possible to input material data inside ANSYS for different materials having different properties in X, Y and Z directions.

Table 3.1.: Material properties for Hexcel ASA-8552

No.	**Material Property**	**Value**	**Unit**
1	Density	1580	Kg m^{-3}
2	Orthotropic Instantaneous Coefficient of		
	Thermal Expansion:		
	(i) Coefficient of Thermal Expansion in X-Direction	1.00E-20	°C $^{-1}$
	(ii) Coefficient of Thermal Expansion in Y-Direction	3.26E-05	°C $^{-1}$
	(iii) Coefficient of Thermal Expansion in Z-Direction	3.26E-05	°C $^{-1}$
3	Orthotropic Elasticity:		
	(i) Young's Modulus X direction	1.35E+11	Pa
	(ii)Young's Modulus Y direction	9.50E+09	Pa
	(iii) Young's Modulus Z direction	9.50E+09	Pa
4	Poisson's Ratio:		
	(i) XY	0.3	
	(ii) YZ	0.45	
	(iii) XZ	0.3	
5	Shear Modulus:		
	(i) Shear Modulus XY	4.90E+09	Pa
	(ii) Shear Modulus YZ	3.27E+09	Pa
	(iii) Shear Modulus XZ	4.90E+09	Pa
6	Orthotropic Thermal Conductivity:		

Continued on next page

Table 3.1 – continued from previous page

No.	Material Property	Value	Unit
	(i) Thermal Conductivity in X direction	5.5	Wm $^{-1\circ}C^{-1}$
	(ii) Thermal Conductivity in Y direction	0.489	Wm $^{-1\circ}C^{-1}$
	(iii) Thermal Conductivity in Z direction	0.658	Wm $^{-1\circ}C^{-1}$
7	Specific Heat, Cp	1300	Jkg $^{-1\circ}C^{-1}$
8	Resin Properties:		
	Fiber volume fraction	0.5742	
	Initial Degree of Cure	0.0001	
	Maximum Degree of Cure	0.9999	
	Gelation Degree of Cure	0.33	
9	Total Heat of Reaction	5.40E+05	J
10	Glass Transition Temperature:		
	Initial Value	2.67	°C
	Final Value	218.27	°C
		0.4708	°C
11	Orthotropic Cure Shrinkage		
	(i) Cure Shrinkage X direction	1.00E-20	mm $^{-1}$
	(ii) Cure Shrinkage Y direction	0.0073	mm $^{-1}$
	(iii) Cure Shrinkage Z direction	0.0073	mm $^{-1}$
12	Orthotropic Liquid Pseudo Elasticity:		
	(i) Young's Modulus X direction	1.32E+11	Pa
	(ii) Young's Modulus Y direction	1.65E+08	Pa
	(iii) Young's Modulus Z direction	1.65E+08	Pa
13	Poisson's Ratio		
	(i) XY	0.346	
	(ii) YZ	0.982	

Continued on next page

Table 3.1 – continued from previous page

No.	Material Property	Value	Unit
	(iii) XZ	0.346	
14	Shear Modulus:		
	(i) Shear Modulus XY	4.43E+05	Pa
	(ii) Shear Modulus XY	4.16E+05	Pa
	(iii) Shear Modulus XY	4.43E+05	Pa

3.5 Creation of Composite Solid Model

To obtain a through thickness cure properties the analysis must be done on a solid composite model. A 3-D finite element solid model was used for this analysis. A shell model was first extracted from the CAD file created using Autodesk FUSION 360. The L-shaped plate was the imported to ANSYS Space-claim platform for creating the shell model. ANSYS Composite Prep-post module was then used to create a composite solid model.

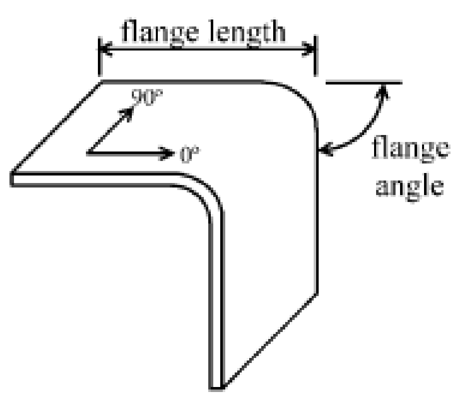

Fig. 3.3.: Composite part geometry

The spring-in for following parameters was analyzed:

- Laminate Thickness
- Part width
- Flange Length
- Cure Cycle

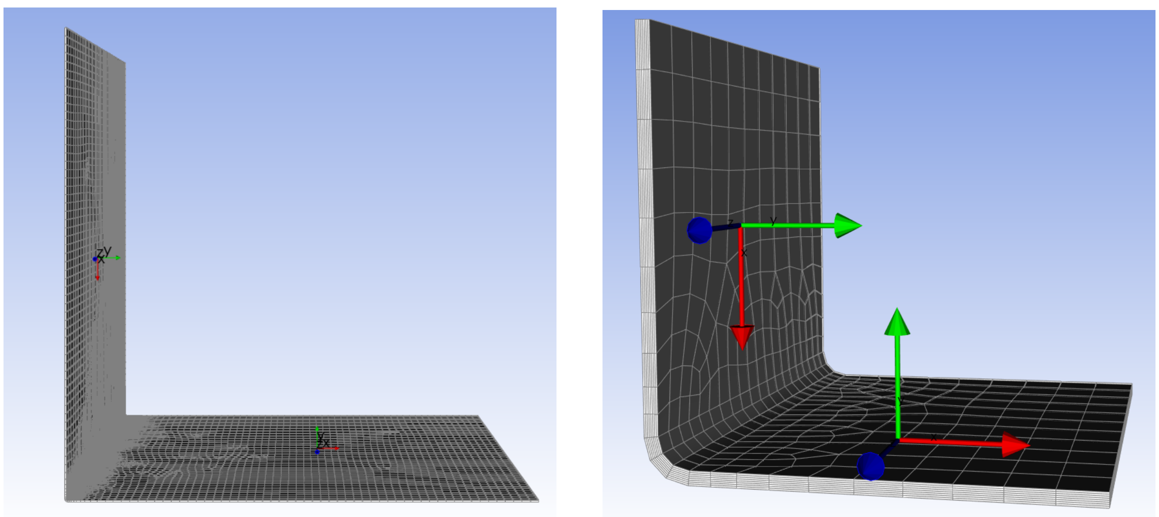

Fig. 3.4.: Composite Solid model of L-shaped plate

3.6 Convergence Study

Mesh generation is an important step in any finite element simulation. In finite-element stress analysis knowing whether key stresses converge and checking if they have converged to a reasonable level of accuracy is important. An acceptable mesh must be used with respect to the shape and size of the elements to achieve results that are reliable when using the finite element method,. The solution accuracy is usually linked with mesh quality and mesh density [14]. Finite element analysis convergence defines the relationship between the number of elements or degree of freedom and the analysis accuracy. Meshing was performed on all the geometries to get accurate results.

3.7 Design of Experiments

The plate dimensions were varied as per the parameters. For the analysis of studying the effect of laminate thickness on spring-in the plate dimensions were kept constant. Number of layers were changed to change the laminate thickness. For analyzing the effects of part width and flange length the part thickness was kept constant as 1mm. The layup sequence was also kept same. Only the width and flange lengths were varied. For the analysis of effects of cure cycle on spring-in the part dimensions were same as the dimensions for the analysis of laminate thickness. Different cure cycles were applied to the part. The following table illustrates the details about solid models used for different analyses.

Table 3.2.: Parameters for software analysis

No.	Parameter	Part Dimensions(mm)	Laminate Thickness	Number of Layers	Layup Sequence
1	Laminate thickness	300×300 × 300	1 mm	8	[0/90]2S
			2 mm	16	[0/90]4S
			4 mm	32	[0/90]8S
2	Part width	300×300 × 300	1 mm	8	[0/90]2S
		300×300 × 1500	1 mm	8	[0/90]2S
		300×300 × 3000	1 mm	8	[0/90]2S
3	Flange Length	300×300 × 75	1 mm	8	[0/90]2S
		300×300 × 150	1 mm	8	[0/90]2S
		300×300 × 225	1 mm	8	[0/90]2S
		300×300 × 300	1 mm	8	[0/90]2S
4	Cure cycle	300×300 × 300	1 mm	8	[0/90]2S

3.8 Transient Thermal Analysis

A 3-step non-linear thermal analysis was performed to obtain the thermal model for the structural analysis later. Newton-Raphson was used to solve the non-linear analysis. The thermal properties such as degree of cure, glass transition temperature and heat of reaction can be obtained here. A convection condition was given to the composite plate as a thermal input load. The convective load resembles the heating process of the composite part. The stepped convection condition characterizes the cure cycle for the composite. Thermal load calculation for the entire cure cycle is carried out and details about material curing, material phase are obtained. It is possible to obtain the DOC results for each individual ply using the simulation which is helpful in predicting the thermal behavior of the composites having layers of two or more different material. This ability makes this methodology unique from other methods presented previously.

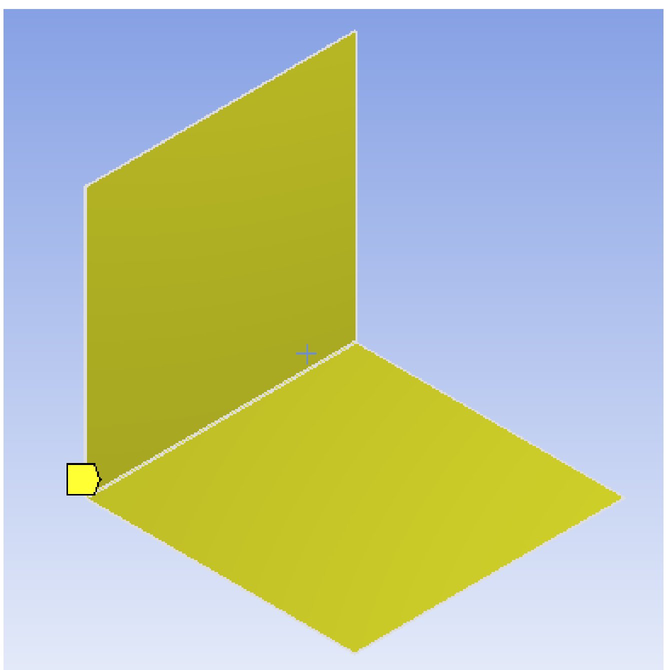

Fig. 3.5.: Thermal load condition for composite plate

Figure 3.5 shows the convective load applied to the composite plate which represents the heating of the composite plate during the curing process.

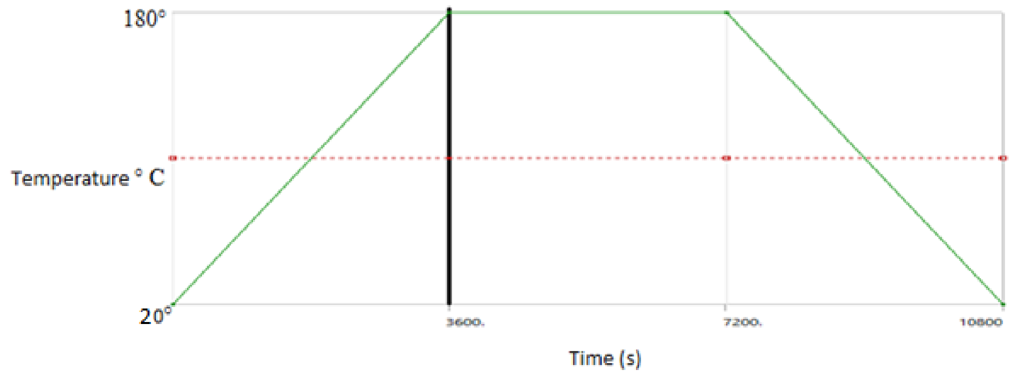

Fig. 3.6.: Single-hold cure cycle (applied temperature vs time plot)

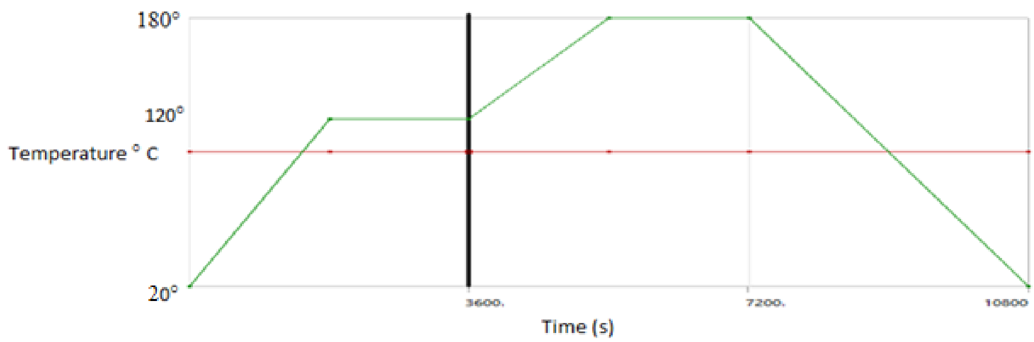

Fig. 3.7.: Two-hold cure cycle (applied temperature vs time plot)

3.9 Static Structural Analysis

Like the thermal analysis a 3-step non-linear structural analysis was performed to obtain the results for process induced residual stresses and shape distortions. The parts were constrained to observe only spring-in and not warpage. A frictionless support and remote displacements were the applied load conditions. A fully cured thermal model was used as the initial boundary condition for the structural analysis. The results of the thermal loads that get applied on the composite part are obtained from the transient thermal module. A support removal action was simulated which imitates the tool removing process for the final step of composite manufacturing.

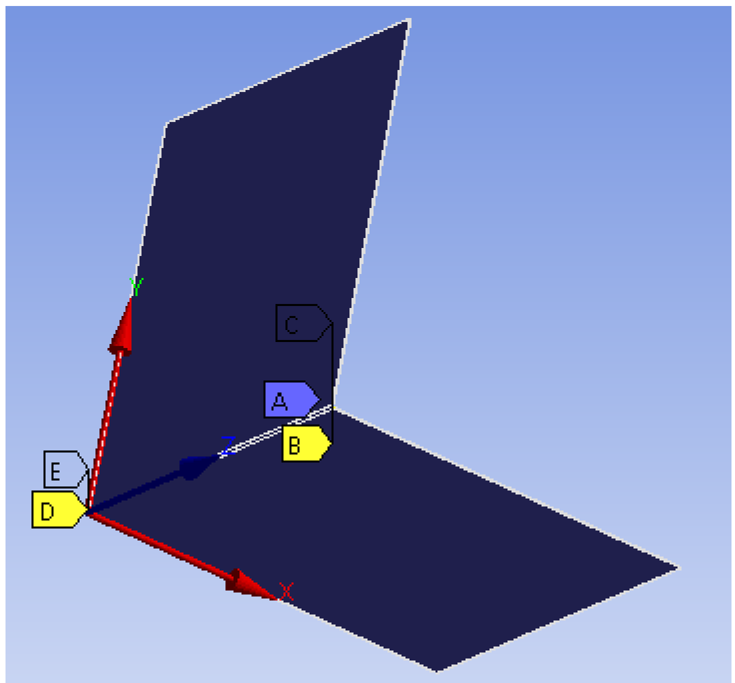

Fig. 3.8.: Applied load conditions for structural analysis

3.10 Manufacturing Process of Composite L-Plate

Composite L-shaped plate was manufactured to verify the spring-in effect. An aluminum tool having dimensions 1 feet length, 1 feet width and 1 feet flange length was used for the manufacturing. Acetone was applied to the tool for having a better surface finish followed by the application of release agent. 4 layers of Gurit woven carbon fiber prepreg were then applied on the tool. Vacuum bagging was done after application of 2 layers to remove the air voids present between the layers. After the application of remaining two layers vacuum bagging was repeated. Then the tool and the composite layers were put in the oven for the curing. A two- hold curing cycle presented above was applied to get a fully cured part. Upon cooling the tool was removed from the part and a final composite L-shaped plate was obtained.

4. RESULTS

To verify the effect of various parameters on spring-in simulations were carried out. ANSYS Composite Cure Simulation was the module used for the simulation. The methodology presented in previous chapter was used to obtain thermal results such as DOC, heat of reaction, glass transition temperature and then structural results such as part deformations and residual stresses.

4.1 Thermal Results

4.1.1 Degree of Cure

With simulation it is possible to obtain the information about composite curing at any point during the curing cycle. Using transient thermal module, the DOC results at the end of every time step were obtained. To study the effect of cure cycle on the composite part distortions, analysis was conducted using two different cure cycles. The first cure cycle was one-step cure cycle where the part was heated from room temperature to 180C and was hold at the same temperature for one hour and then was cooled to the room temperature. The three phases of the curing were assumed as liquid phase of the resin, gel phase of resin and the glassy solid phase of resin where the part is completely cured. The values of DOC at end of each time step were obtained from the software for the single-hold cure cycle. Figure 4.1 (a) shows the tabular data for the DOC at end of each time step. Figure 4.1 (b) is the plot of all the points from the tabular data for DOC from figure 4.1 (a)

The second cure cycle was a two-hold cure cycle where the part was heated from room temperature to 120 °C, held for half hour and then again heated to 180 °C and again held at the same temperature for half hour and then was cooled down to the room

Time [s]	Minimum	Maximum	Average
240.	1.0022e-004	1.0022e-004	1.0022e-004
480.	1.0117e-004	1.0117e-004	1.0117e-004
720.	1.0377e-004	1.0378e-004	1.0378e-004
960.	1.0991e-004	1.0992e-004	1.0992e-004
1200.	1.2354e-004	1.2357e-004	1.2355e-004
1440.	1.5316e-004	1.5322e-004	1.5318e-004
1680.	2.1786e-004	2.1802e-004	2.1793e-004
1920.	3.6347e-004	3.6382e-004	3.6361e-004
2160.	7.0575e-004	7.0659e-004	7.061e-004
2400.	1.5455e-003	1.5476e-003	1.5464e-003
2640.	3.6669e-003	3.6722e-003	3.6691e-003
2880.	9.0809e-003	9.0945e-003	9.0866e-003
3120.	2.2771e-002	2.2805e-002	2.2785e-002
3360.	5.6353e-002	5.6435e-002	5.6387e-002
3600.	0.13392	0.1341	0.13399
3840.	0.29327	0.29362	0.29342
4080.	0.46722	0.46754	0.46735
4320.	0.61092	0.61116	0.61102
4560.	0.71332	0.71349	0.71339
4800.	0.78126	0.78136	0.7813
5040.	0.82059	0.82065	0.82062
5280.	0.84138	0.84141	0.84139
5520.	0.85404	0.85406	0.85405
5760.	0.86287	0.86289	0.86288
6000.	0.86956	0.86958	0.86957
6240.	0.87492	0.87493	0.87492
6480.	0.87937	0.87937	0.87937
6720.	0.88315	0.88316	0.88316
6960.	0.88645	0.88645	0.88645
7200.	0.88935	0.88936	0.88936
7440.	0.89195	0.89196	0.89196
7680.	0.89229	0.89229	0.89229
7920.	0.89233	0.89233	0.89233
8160.		0.89234	
8400.			
8640.			
8880.			
9120.			
9360.			
9600.			
9840.			
10080			
10320			
10560			
10800			

Fig. 4.1.: (a) DOC results for each time step (single-hold cure cycle)

temperature. Similar to the one-hold cure cycle, DOC results at the end of each time step were obtained and plotted on a graph.

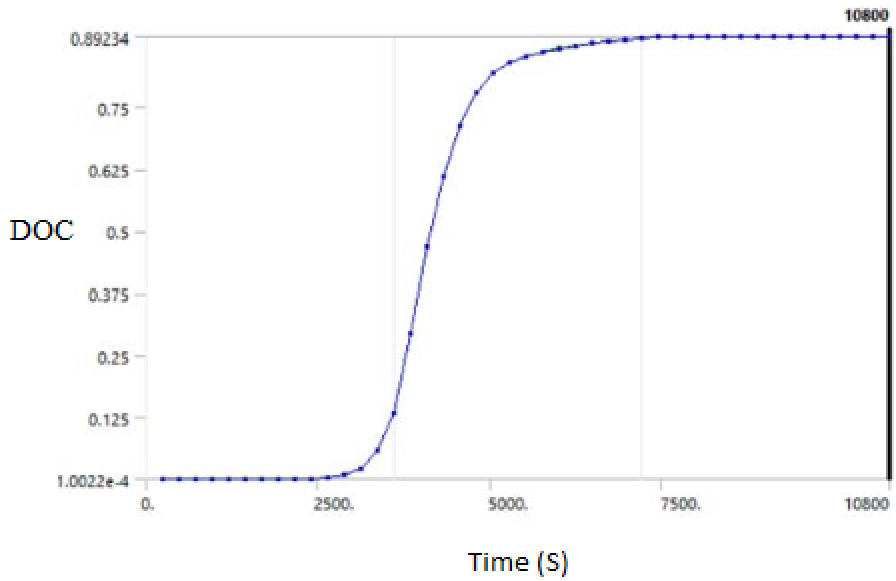

Fig. 4.1.: (b) DOC vs time plot for single-hold cure cycle

Figure 4.2 (a) and (b) represent the tabular data of DOC at the end of each time step for a two-hold cure cycle and the plot of DOC against the time for two-hold cure cycle. The effect of cure cycle on DOC can clearly be observed here from both the plots in figure 4.1 and figure 4.2. It is visible that for the single-hold cure cycle the resin was cured faster than it was cured with a two-hold cure cycle. Effect of this variation of DOC due to change in cure cycle can also be observed while analyzing the spring-in.

Figure 4.3 shows the results for DOC for composite part. It is evident that the outer plies are cured before the inner plies as the heat is being applied from outside. These results also demonstration the accuracy of the simulation.

Time [s]	Minimum	Maximum	Average
240.	1.0022e-004	1.0022e-004	1.0022e-004
480.	1.0147e-004	1.0148e-004	1.0147e-004
720.	1.055e-004	1.0551e-004	1.055e-004
960.	1.1657e-004	1.166e-004	1.1658e-004
1200.	1.4533e-004	1.454e-004	1.4536e-004
1440.	2.1945e-004	2.1964e-004	2.1953e-004
1680.	4.1741e-004	4.1793e-004	4.1763e-004
1920.	9.7976e-004	9.8126e-004	9.8039e-004
2160.	2.1935e-003	2.1966e-003	2.1948e-003
2400.	4.0074e-003	4.0117e-003	4.0092e-003
2640.	6.4523e-003	6.458e-003	6.4547e-003
2880.	9.5433e-003	9.5503e-003	9.5462e-003
3120.	1.3285e-002	1.3293e-002	1.3288e-002
3360.	1.7674e-002	1.7684e-002	1.7678e-002
3600.	2.2704e-002	2.2715e-002	2.2708e-002
3840.	2.836e-002	2.8372e-002	2.8365e-002
4080.	3.7671e-002	3.7691e-002	3.768e-002
4320.	5.3156e-002	5.3189e-002	5.317e-002
4560.	7.9052e-002	7.9107e-002	7.9075e-002
4800.	0.12216	0.12225	0.12219
5040.	0.19219	0.19233	0.19225
5280.	0.29976	0.29997	0.29985
5520.	0.44842	0.4487	0.44854
5760.	0.59669	0.59693	0.59679
6000.	0.70355	0.70372	0.70362
6240.	0.77506	0.77516	0.7751
6480.	0.81731	0.81737	0.81734
6720.	0.83955	0.83958	0.83956
6960.	0.85284	0.85286	0.85285
7200.	0.86199	0.86201	0.862
7440.	0.86888	0.86889	0.86889
7680.	0.86973	0.86974	0.86974
7920.	0.86984	0.86985	0.86984
8160.	0.86985	0.86986	0.86985
8400.			0.86986
8640.			
8880.			
9120.			
9360.			
9600.			
9840.			
10080			
10320			
10560			
10800			

Fig. 4.2.: (a) DOC results for each time step (two- hold cure cycle)

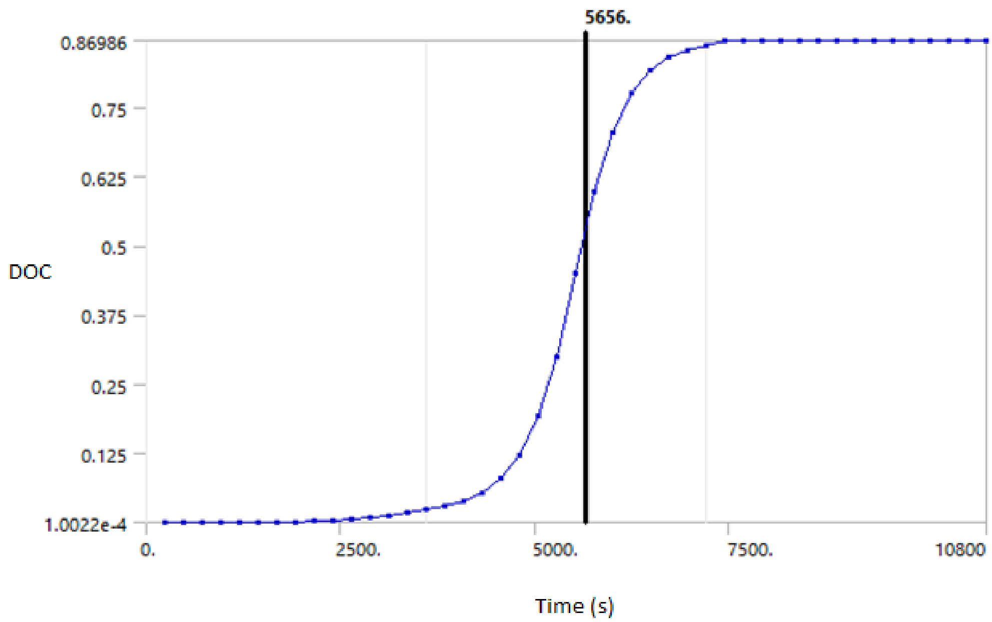

Fig. 4.2.: (b) DOC vs time plot for two-hold cure cycle

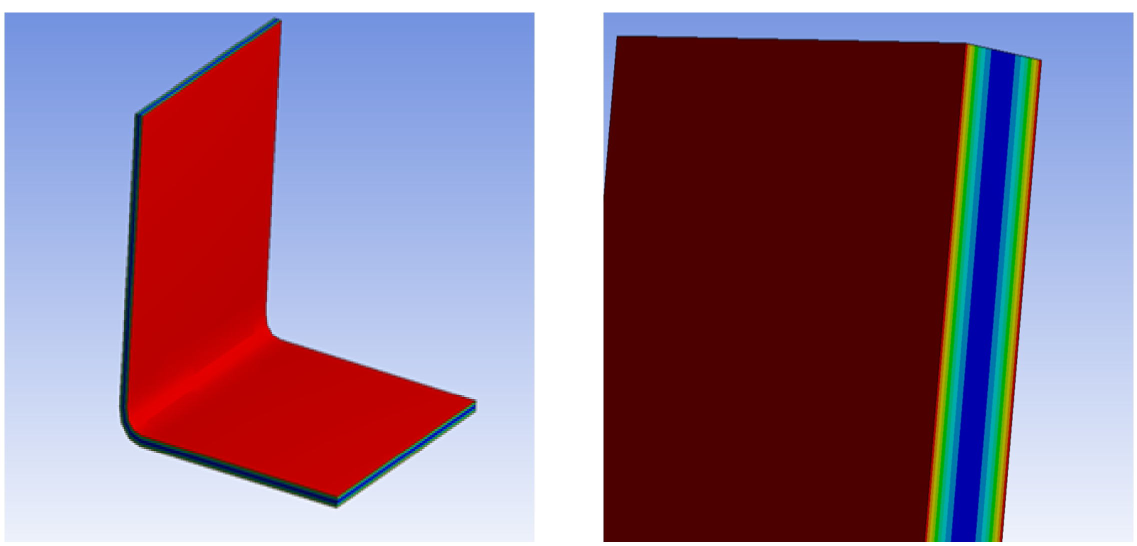

Fig. 4.3.: Ply-wise DOC results

4.1.2 Glass Transition Temperature

The following plot shows the progression of glass transition temperature (Tg) throughout the cure cycle (two-hold). From these results the phase change of the resin can be analyzed. The resin converts from liquid phase to a rubbery phase when gelation occurs. The resin then converts to a glassy solid state. The glass transition temperatures at both these phase changes can be obtained from these results which help in predicting the material phase at any specific point during the cure cycle.

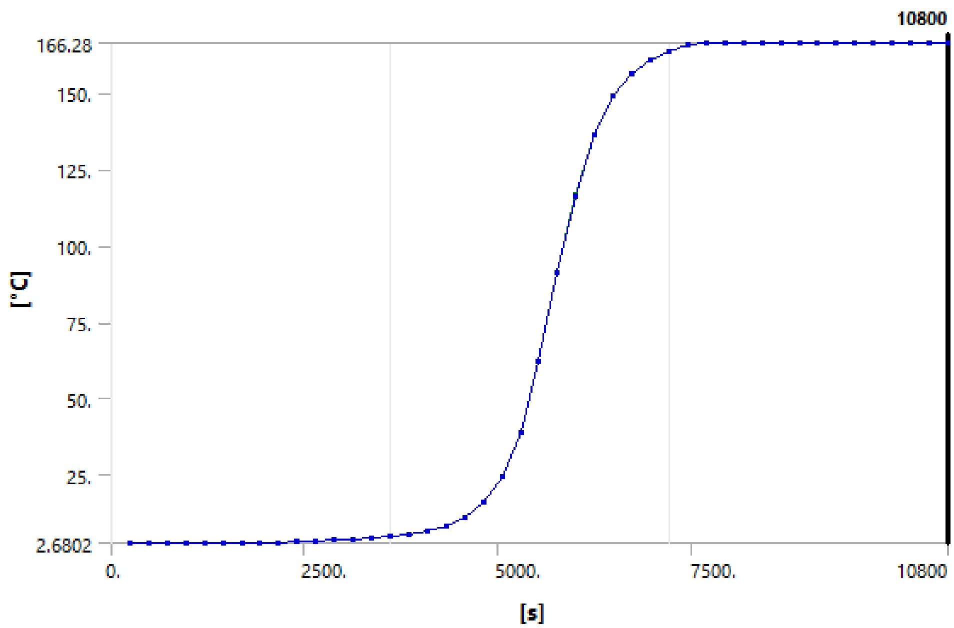

Fig. 4.4.: Tg vs time plot for two-hold cure cycle

4.1.3 Heat of Reaction

Results for the heat of reaction are presented below in figure 4.5. The plot of Heat of reaction against the time shows the total heat of reaction throughout the cure cycle. Composite curing being an exothermic reaction, heat of reaction is seen to be increasing during the second phase of the cure cycle where the resin is in gel phase. The heat of reaction then decreases as the part is cured and a drop in the heat of reaction can be seen. The curve becomes a plateau as the part is fully cured.

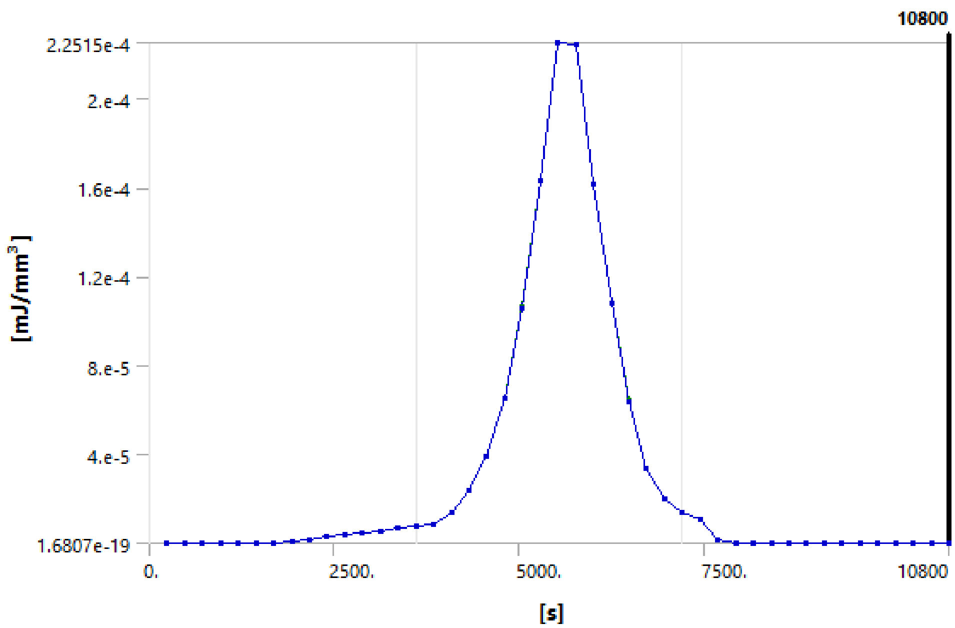

Fig. 4.5.: Heat of Reaction vs time plot for two-hold cure cycle

4.2 Residual Stresses

Since analytical calculation of process induced residual stresses is a time consuming and difficult process, obtaining the results for residual stresses through simulation is a comprehensive technique. The residual stresses induced due to thermo-mechanical curing process are obtained in the form of contour plot of the composite part. Following figure shows the induced residual stress distribution in the composite laminate. Just like the thermal module structural module also provides the stresses induced in each individual ply. This pre-loading stresses over the composite parts can make the part weaker upon loading. The results for residual stresses are the stresses present in the part post deformation. Even if the part is deformed to get rid of stresses generated during the curing process, there are stresses present in the part post deformation. It is practically impossible to get rid of all the residual stresses as the stresses are trapped in the composite laminate during phase change of the resin. These stresses can be predicted and can be used as the initial stress condition for the part while the part is further analyzed for practical load conditions such as crash, impact and torsion or bending.

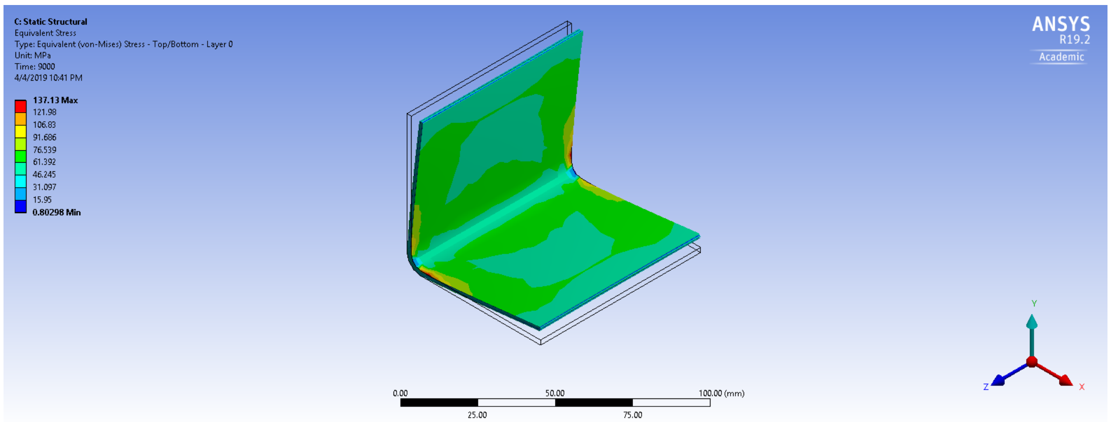

Fig. 4.6.: Residual stress contour for the composite laminate

4.3 Spring-in

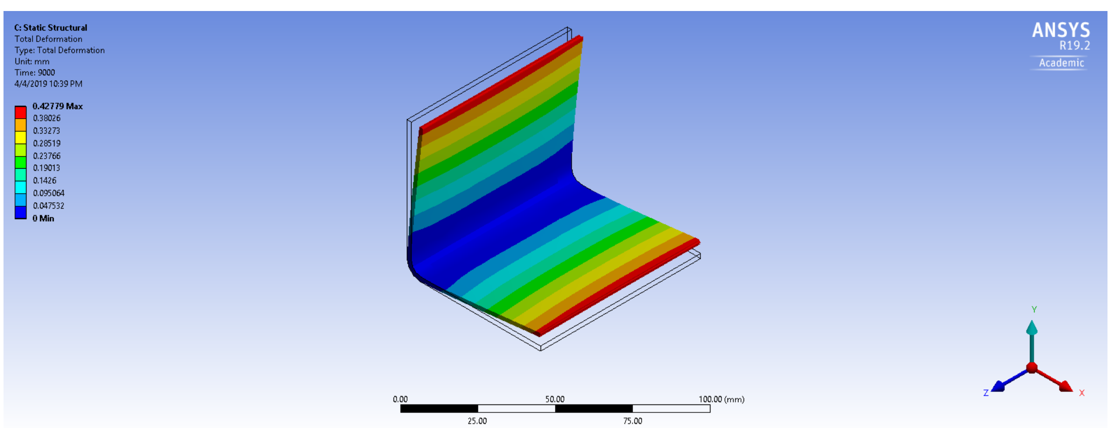

Fig. 4.7.: Spring-in for L-shaped composite plate

Simulation results for spring-in of a L-shaped plate provide the accurate part shape post curing. In this study various parameters which affect the composite shape were examined. A comparative assessment of all the parameters gave a good correlation with the experimental results that were available in previous studies.
Figure 4.7 shows the deformed L-shaped composite plate post curing. The change in angle can clearly be observed. The values of the spring-in angle are obtained from the simulation results. It is possible to acquire the direction deformation for the laminate using this technique as well. It was detected that spring-in varies with variation in parameters. As previously mentioned, the parts were analyzed for four parameters. Laminate thickness, flange length, width of the part and the cure cycle were the parameters against which the simulations were carried out.
Table 4.1 provides the results for the variation in spring-in for varying parameters. It is evident that with increase in laminate thickness the spring-in decreases. Most of the previous studies had demonstrated this relation between laminate thickness and spring-in angle. Although few studies presented that with increase in laminate thickness the spring in angle is increased, there are adequate experimental results which support the trend obtained in simulation results.
Also, when the width of the part is increased the spring-in angle seems to be declining. The warpage effect is more observable in wider part than the spring-in effect. However, as the parts were constrained in a way to only observe spring-in effects warpage effects can be assumed to be negligible in wide parts. Although, accuracy of the results for wide parts may get hindered due to this.

Reducing the flange length can effectively reduce the spring-in effects in composite angular parts. However, it cannot be an effective solution as the part geometries are dependent on the assembly of the structures. The simulation results showed that with Increase in flange length the spring-in angle also increases.
Thermal model simulation results showed that in single-hold cure cycle cured the composite part quicker than a two-hold cure cycle. Similar trend was observed for

Table 4.1.: Variation in spring-in as per varying parameters

Sr. No.	Parameter	Variation in Parameter	Laminate Thickness	Number of Layers	Spring-in Angle
1.	Laminate thickness	1 mm	1 mm	8	1.15
		2 mm	2 mm	16	0.98
		4 mm	4 mm	32	0.83
2.	Part width	300 mm (1 ft)	1 mm	8	1.15
		1500 mm (5 ft)	1 mm	8	0.95
		3000 mm (10 ft)	1 mm	8	0.89
3.	Flange Length	75 mm	1 mm	8	0.98
		150 mm	1 mm	8	1.06
		225 mm	1 mm	8	1.10
		300 mm	1 mm	8	1.15
4.	Cure cycle	One-hold	1 mm	8	1.03
		Two-hold	1 mm	8	1.15

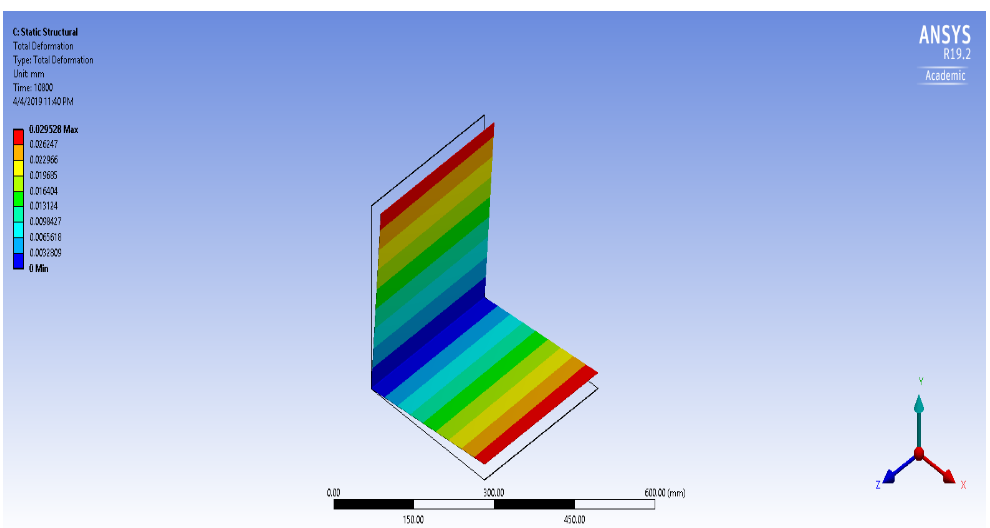

Fig. 4.8.: (a) Spring-in parameter: Laminate Thickness (1 mm)

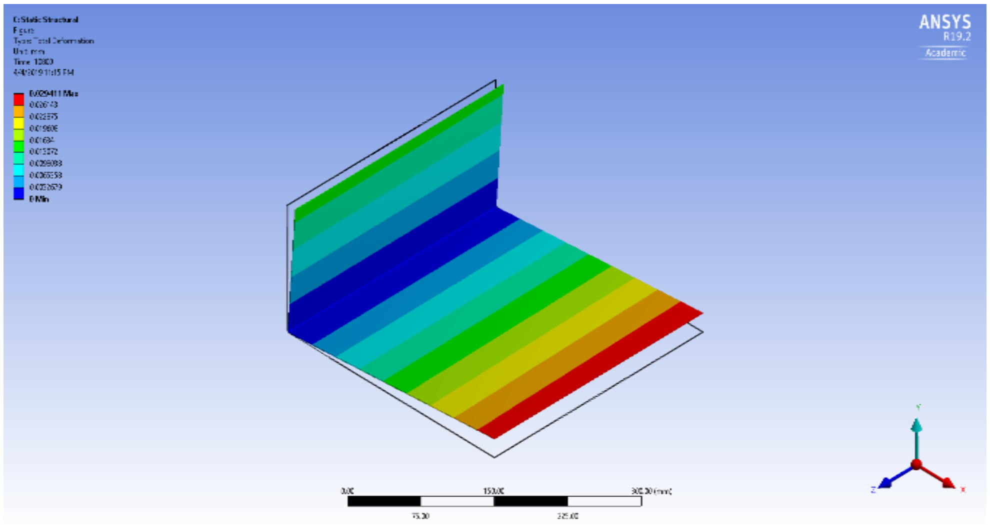

Fig. 4.8.: (b) Spring-in parameter: Flange Length (150 mm)

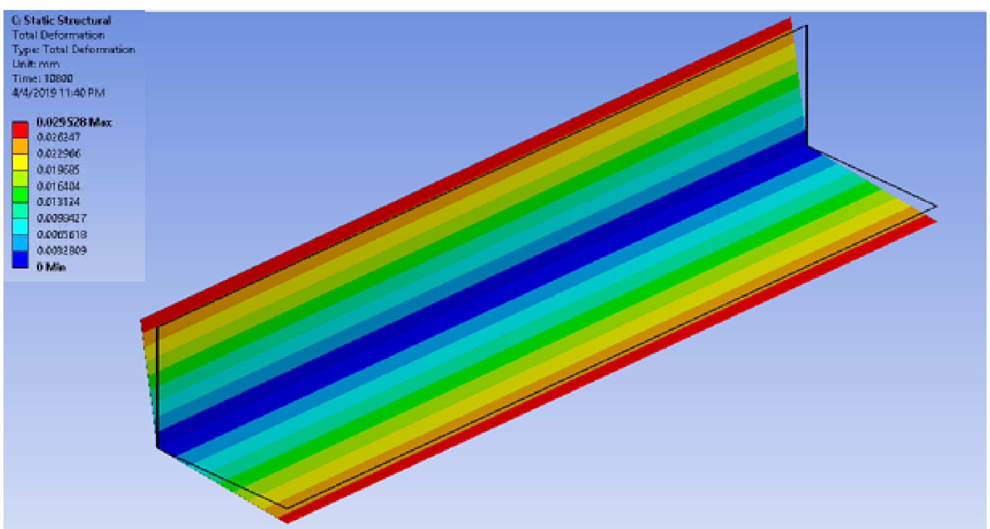

Fig. 4.8.: (c) Spring-in parameter: Part Width (5 ft)

the spring-in angles as well. It is seen that spring-in angle for single-hold cycle was less than that for a two-hold cure cycle. Quicker curing may decline the development of residual stresses which ultimately results in spring-in angle being less for a single-hold cure cycle.

4.4 Validation of the Methodology

The methodology presented here was validated by comparing the spring-in results obtained by simulation with the experimental results that were presented by various researchers whose work was reviewed. The simulation results showed a similar trend as the experimental results as simulation was carried out for various parameters. In some cases, the spring-in values achieved from simulation results were found to be more accurate than the analytically calculated spring-in values.

LMAT [15] conducted experiments to verify effect of laminate thickness on spring-in angle. The trend in the LMAT results was similar to the simulation results obtained using the methodology presented here.

Figure 4.9 shows that with increase in laminate thickness spring-in angle is reduced in both experimental and simulation results. The difference between the experimental and simulation spring-in value was due to the fact that effect of warpage and effect of tool-part interaction were neglected in this particular case while simulating the curing process and applying the structural loads.

Carolyne Albert, Goran Fernlund [16] presented a model where an analytical model was developed to calculate the spring-in for L-shaped and C-shaped composite parts. The simulation results provided results closer to experimental results presented in this particular study than the analytically obtained spring-in values. Figure 4.10 shows the simulaton results of spring-in in a C-shaped composite part. Table 4.2 shows the comparison between analytical, simulation and experimental values of the spring in. The analytical and experimental values were obtained from the Carolyne Albert, Goran Fernlund model.

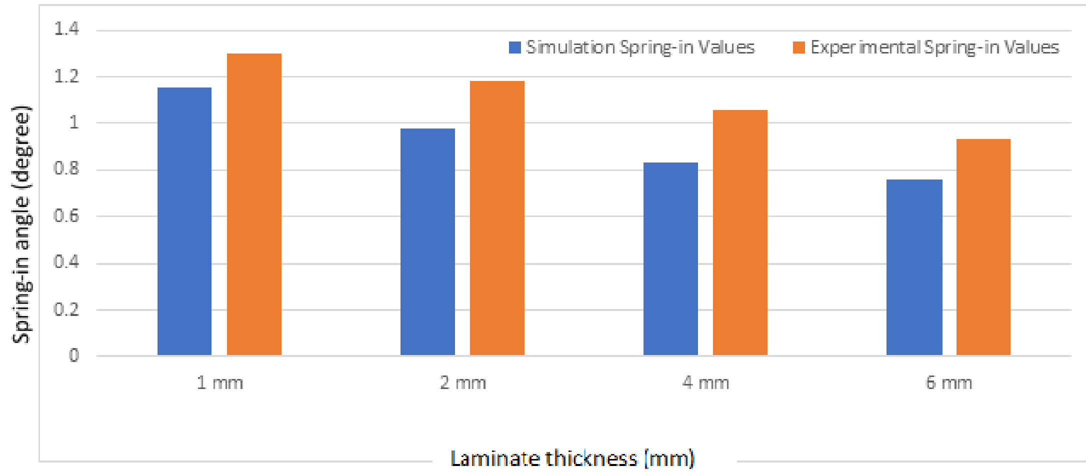

Fig. 4.9.: Comparative plot of simulation and experimental results of spring-in angle vs. laminate thickness

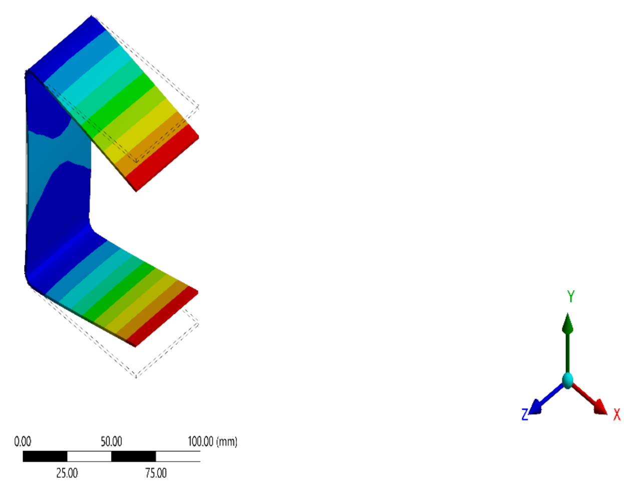

Fig. 4.10.: Spring-in for C-shaped composite plate

Table 4.2.: Comparison between analytical, simulation and experimental values of the spring in

Analytical Value	Simulation value	Experimental Value
0.90	0.81	0.78

For validating the results for other parameters there were no significant previous results available. Future recommendation for this study would be to validate all these parameters by manufacturing all the parts with parameters defined here.

4.5 Prediction of Three-directional Shape Distortions

Effect of warpage/bending in wider parts can also be analyzed using the method presented in this thesis. Wider parts show more warpage or bending of the flat surfaces. ACCS can be effective tool to analyze the warpage in wider commercial parts such as gurney flaps or wider composite panels, ribs, roofs etc.

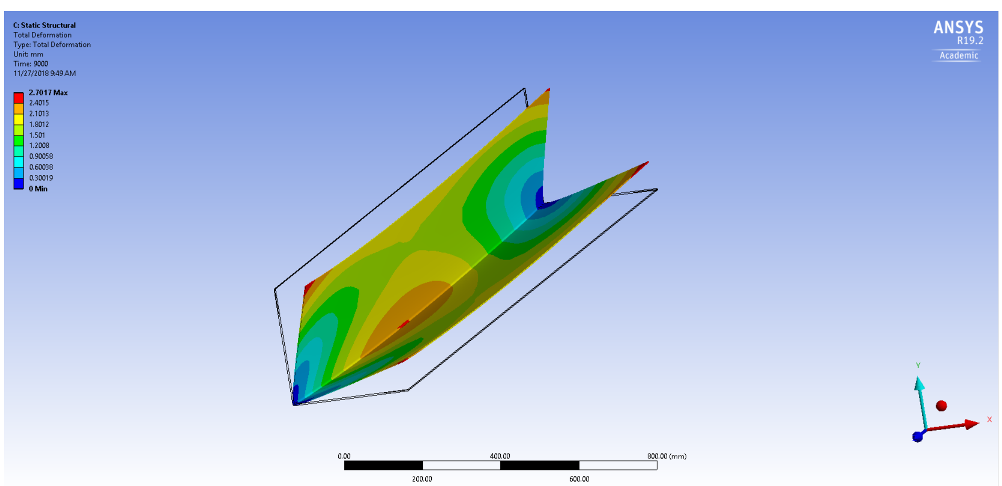

Fig. 4.11.: Warpage effect in wider L-shaped composite plate

Figure 4.11 shows the bending in the L-shaped composite plate which is 10 feet wider. Warpage in both vertical and horizontal surface can be observed here. Usually tool-part interaction is responsible for the warpage effect occurring. It is possible to model the effects of using different tool on the warpage and bending of composite plate. ACCS assists to analyze the 3-directional dimensional changes in composite parts. This ability is unique as most of the previous methods were good for obtaining the results for 2-directional dimensional changes. With this ability analyzing the development of residual stresses in commercial composite parts with complex geometries is feasible.

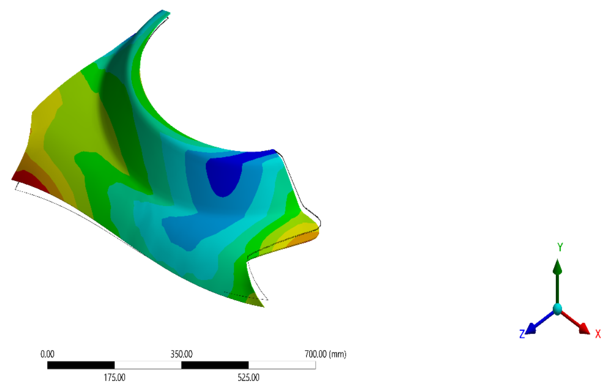

Fig. 4.12.: (a) Shape Deformations in composite front fender of an automobile

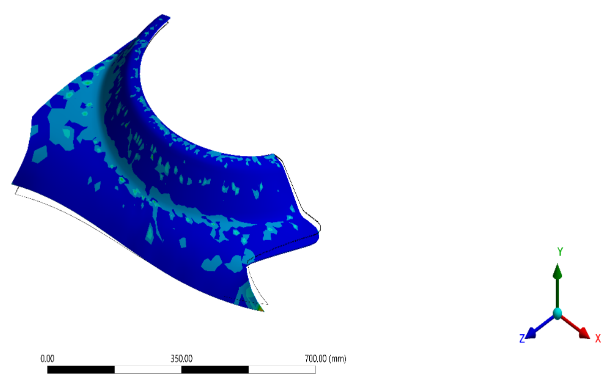

Fig. 4.12.: (b) Residual stresses in composite front fender of an automobile

Figure 4.12 (a) and figure 4.12 (b) show the capability of the methodology to be a ground-breaking technique in commercial composite manufacturing for predicting the final shape of the composite part.

5. CONCLUSION AND FUTURE WORK

5.1 Conclusion

Predicting the final shape of any composite part post curing has become crucial in recent years. This thesis has provided a comprehensive methodology to predict the process induced shape distortions accurately and in less time. The ability to predict the final shape of the part before tool design is helpful in reducing the manufacturing cost. Although several previous studies have emphasized using finite element analysis for predicting the shape distortions, all the methods had several limitations. This study has proposed a comprehensive methodology to predict the final shape of the composite part not only for simple flat panels but also for complex composite parts using ANSYS Composite Cure Simulation (ACCS).

This thesis presented the thermal results for composite parts during cure. This helped in obtaining the results for all the thermal properties. While previous studies provided the structural results for spring-in this thesis presented both thermal and structural results. When compared with experimental results previously presented, the simulation results obtained here were observed to be more accurate than analytically calculated results.

The methodology developed here was found to be accurate, less time consuming and effective for further analysis of the composite parts for various practical purposes. This technique may open a new window in composite manufacturing with its extraordinary accuracy. Also, the ability of using the deformed model for further mechanical analysis such as crash analysis or analysis for various load cases makes this technique unique.

5.2 Future Scope

The future extensions for the presented method can be as following:

- The present study does not take effect of friction between the tool and the composite part. However, using simulation it is possible to model the effects of the friction between the tool and the composite part.

- The simulation results for few of the parameters were compared with the experimental results presented in literature referred. For validation of all the parameters experiments can be conducted for varying the flange lengths and widths of the L-shaped plates.

- For validating the effect on one-hold cure cycle and two-hold cure cycle the parts can be manufactured and different cure cycles can be applied to study the effects of cure cycle on spring-in.

- The shape deformation can be performed on various complex geometries. The analysis of crash structures can be revolutionary. It is possible to perform a comparative crash analysis with undeformed and deformed geometry.

- Analyze warpage as well as bending in composite parts post curing using this methodology.

- Compensate the spring-in during tool design and perform multiple iterations to obtain an accurate final shape of the desired composite part.

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