INFLUENCE OF THE FORMING PROCESS ON THE SHAPE DISTORTION OF A COMPOSITE C-SHAPED AEROSPACE SPAR

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Abstract

Shape distortions are generally considered influenced by several factors including thermal contraction, curing kinetics, fibre content, lay-up (balanced / unbalanced) and anomalies developed during manufacturing. In this work influences from forming on the shape distortion of a C-shaped composite spar with a recess area on one side is investigated. The forming influences considered are fibre angle deviation, inbuilt residual fibre compression (RF compression) and inbuilt residual fibre tension (RF tension). Abnormalities due to various stacking sequences and choice of lay-up process are especially focused upon.

1 Introduction

The shape distortion of a generic C-shaped composite spar is commonly seen as a change in the flange angle (known as a spring-in) and, in some cases, a twist. Spring.-in, is the change of external angle of a symmetric and balanced lay-up, illustrated in Figure 1. Shape distortions are generally considered influenced by several factors including thermal contraction, curing kinetics, fibre content, lay-up (balanced / unbalanced) and anomalies developed during manufacturing, as e.g. corner thinning / thickening [1], [2]. All these factors are greatly influenced by the manufacturing process, also the lay-up, since forming of continuous fibre reinforcement into complex shapes changes the initial fibre angles. Normally, influences from forming and manufacturing anomalies are left out from spring back simulations due to lack of input information and since they very much depend on the forming process.

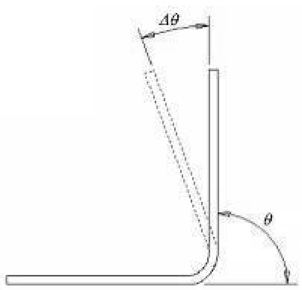

Figure 1. Illustration of spring-in.

Cost effective forming of geometrically complexly shaped structures is of fundamental importance for the production of future composite articles. For aerospace components automated tow placement (ATP) or hot drape forming (HDF) of pre-stacked material provide two good alternatives to traditional hand layup. While for ATP, the fibre layup angles are specified by the soft-ware, both HDF and hand-layup suffer from fibre angle deviations compare to the flat laminates due to forming.

A general problem when forming a quasi-isotropic unidirectional (UD) prepreg lay-up over a double curved geometry is out-of plane wrinkling because of fibre compression. In previous work [3], [4] it has been shown that forming of a C-shaped composite spar, containing a recess area (see figure 2), with different lay-up sequences will result in different behavior in terms of inbuilt fibre compression and inbuilt fibre tension (see figure 3 and 4). Inbuilt fibre compression results in out-of plane wrinkling.

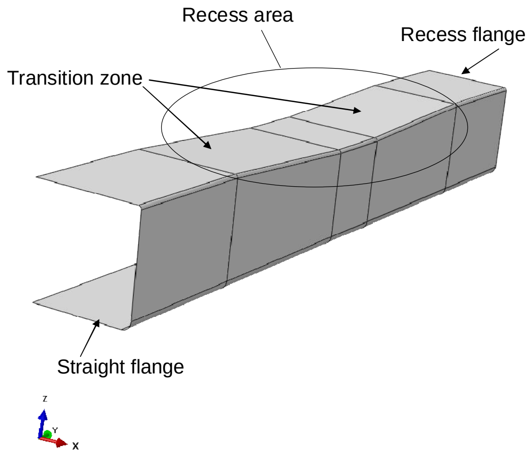

Figure 2. Spring-in of a C-shaped spar

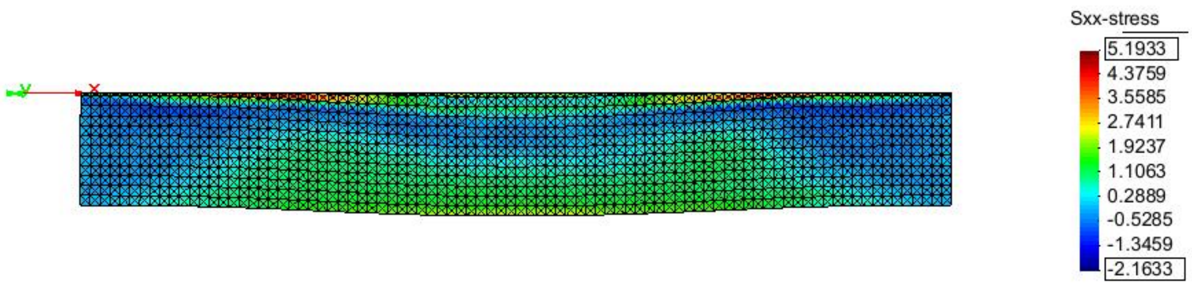

Figure 3. Aniform simulation of C shaped spare with recess area showing inbuilt fibre compression [4].

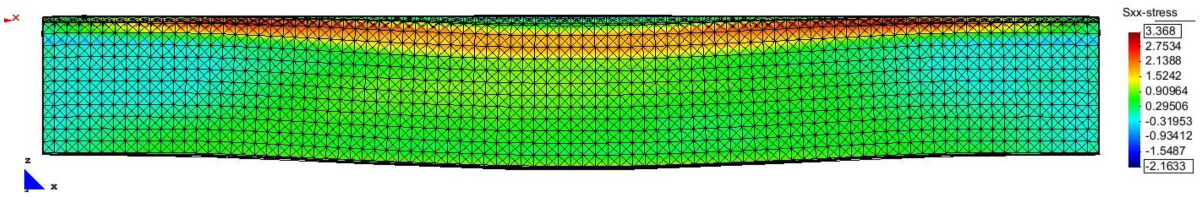

Figure 4. Aniform simulation of C shaped spare with recess area showing inbuilt fibre tension [4].

In this work influences from forming on the shape distortion of a C-shaped composite spar with a recess area on one side (see figure 2) is investigated. The forming influences considered are fibre angle deviation, inbuilt residual fibre compression (RF compression) and inbuilt residual fibre tension (RF tension). Abnormalities due to various stacking sequences and choice of lay-up process are especially focused upon. The studied material system is an aerospace graded, unidirectional prepreg material that may be pre-stacked using automated tape layup (ATL) and forming is perform using either hand lay-up or HDF of the pre-stacked prepreg lamina.

2 Experimental

An experimental study on spring-in (as illustrated in figure 1) was performed on a spar with a recess area in one flange (geometry according to figure 2 and table 1). The geometry was chosen to create 3-D forming. The spars were Hot Draped Formed (HDF) with parameter settings in accordance with table 1. The parameters were chosen to create different level of axial loading and deformation during the forming.

Spar length [mm]	480
Web width [mm]	70
Flange length [mm]	55
Chamfer length [mm]	125
Chamfer depth [mm]	6.25
Nominal thickness [mm]	4.192
Radius recess flange [mm]	2
Radius Straight flange [mm]	6

Table 1. Spar geometry

2.1 Material

A 180°C cure epoxy prepreg with IM fibre and approximately 57% fibre content was used in the experiments. The epoxy prepreg had a Cured Ply Thickness (CPT) of 0,131 mm and contained unsolved thermoplastic toughener in the matrix [5].

2.2 Lay-up

Two different lay-ups were used: A=$[(45,0,135,0)_n]_s$ with the purpose to, theoretically, obtain fibre compression and B=$[(90,45_2,135_2,90,0_2)_n]_s$ with the purpose to obtain fibre tension [3], [4]. Some of the material was consolidated in 70°C and 6 bar pressure to obtain full impregnation before use. The consolidation was performed on the plies before lay-up with the purpose of increasing the inter-ply friction [5] and minimizing the "bulk effect" defined as the difference between the lay-up thickness and the Cured Ply thickness. A sum-up of the investigated parameters is presented in table 2.

Sample ID	CPT [mm]	Lay-up	Impregnation level
AtF	t=0.131	$A=[(45,0,135,0)_4]_s$	F=Full
AtN	t=0.131	$A=[(45,0,135,0)_4]_s$	N=Normal
BtF	t=0.131	$B=[(90,45_2,135_2,90,0_2)_2]_s$	F=Full
BtN	t=0.131	$B=[(90,45_2,135_2,90,0_2)_2]_s$	N=Normal

Table 2. Lay-up parameters

2.3 Forming of spars

The spars were formed by stacking flat laminas according to the test matrix, table 2. The pre-stacked lamina was thereafter placed on top of the mould, where after the vacuumbag was loosely sealed on top of the lamina. After heating up to 65°C , vacuum was applied forcing the material to form towards the mould. The vacuum was held until the lamina temperature was back at room temperature.

2.4 Cure assembly

A cure assembly where the tension in the vacuum bag was reduced by folds was used in purpose to minimize the corner effects in terms of radius thinning.

2.5 Cure cycle

All components were cured in an autoclave with an identical cure cycle: 7bar, heating (1.5°C/min) to 180°C and hold for 2h followed by cooling (3°C/min).

2.6 Measurements

The radius thicknesses of each component were measured in a micrograph section in the middle of the spar. A micrograph section was also used to measure the wrinkle height in the recess area. The wrinkle height was measured as the height of the wrinkle for the 3rd ply from the inside of the flange.

The geometry shape was measured in a coordinate measuring machine (CMM) and the spring-in ($\Delta\theta$) was calculated from the measurement result. The spar was defined as 480 mm long and the angle measurements were made in cross sections 82, 133, 189 and 237 mm from the spar edge. The values for $\Delta\theta$ were normalized to the FE-modeled value for $\Delta\theta$, 82 mm from the edge.

3 FE-modeling

A simplified material model that accounts for the relevant mechanisms during cure was used in this work [6], [7], [8]. This methodology only requires basic material data e.g. stiffness properties and coefficients of thermal expansion. A typical spring-in result using the simplified is shown in figure 5.

A suitable element mesh was required of the article. The final mesh shown consists of three dimensional 20-node solid elements (C320R in Abaqus), the number of nodes were 94005 and 16800 elements with a suitable elements around the radius and through the thickness. To prevent rigid body motion the spar was supported at three points, two in the front and one in the back. A typical spring-in result using the simplified

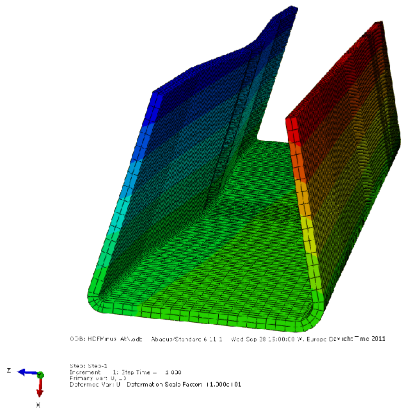

Figure 5. Typical spring-in result for B-layup.

3.1 Material properties and initial conditions

The typical lamina properties in table 3, valid at RT, have been used in the analysis of the C-spar. The lay-up both for the web and for the flanges were 50/50/0% for the A-layup and for the B 25/50/25 % in the 0°/45°/90° direction.

Material Type	Carbon prepreg
El(GPa)	145
Et(GPa)	8
Glt(GPa)	4
ν (–)	0.3
Ply thickness (mm)	0.13

Table 3. Ply properties

In the analysis a temperature change representing the cooling of the component from the cure temperature to room temperature was used to create the shape distortions. When just the temperature is accounted, the shape distortion is under estimated because many important factors are neglected e.g. the chemical shrinkage of the polymer. For that reason the coefficient of thermal expansion through the thickness have been replaced by a coefficient of process expansion, CPE as,

$$\frac{\Delta\theta}{\theta} = (\alpha_\theta - CPE)\cdot\Delta T \qquad (1)$$

In order to find a proper value of CPE results from a process trial or other components are needed. The temperature change is -160°C as a result from cooling from the cure temperature of 180°C to room temperature.

The fiber angles used in the FE-model were determined using a standard draping facility in the soft-ware (Composite Modeler). According to this analyze, the fiber angles in the transition zone deviated 2.86° for the 0°-ply, the 45°-ply and the 135°-ply (see figure 6).

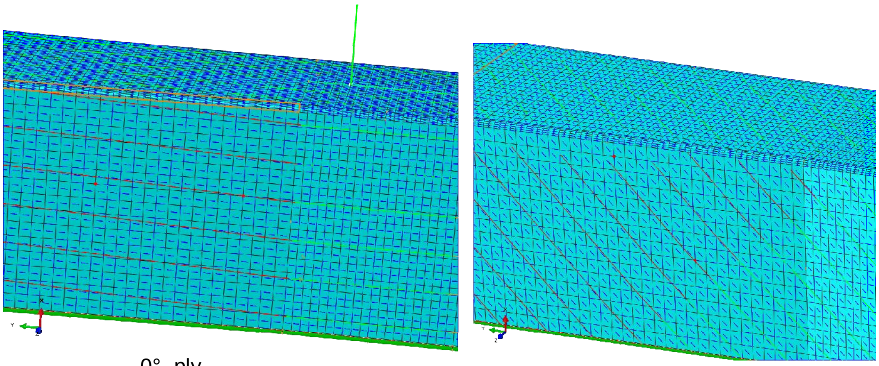

Figure 6. Fiber angle deviation in the transition zone.

3 Results

Results from manufacturing of the spars are presented in table 4, figure 7 and figure 8. The radius thicknesses for all the samples were in the close range of CPT.

The normalized values for the calculated and the measured spring-in are presented in figure 9 and 10. As shown the correlation between the calculated and the experimental spring-in are very good for the straight flange with the B lay-up and fairly good for the straight flange with the A lay-up. The recess flange for both the A and the B lay-up showed not so good correlation between the calculated and the experimental spring-in. The difference between the calculated and the experimental spring-in, in the recess area, is in the same range for both the A and B lay-up. As a reference the calculated spring in for the B lay-up is approximately 0.1° larger than for the A lay-up which is similar to the experimental results for the straight flange.

Sample ID	**Wrinkle height [mm]**	**Radius thickness [mm]**	**Normalized Spring-in [°]**
AtF	1.62	4.13	See figure 9
AtN	1.76	4.15	See figure 9
BtF	No defect	4.29	See figure 10
BtN	No defect	4.02	See figure 10

Table 4. Results

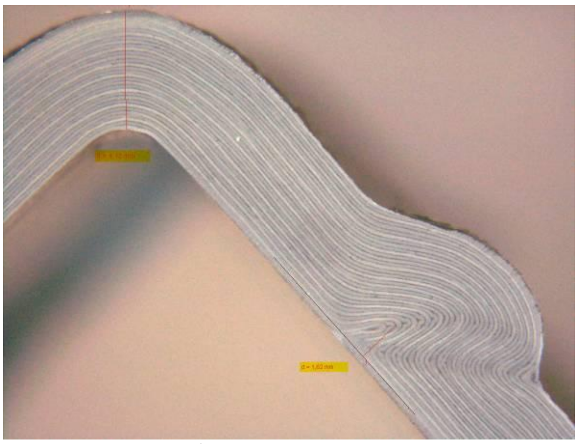

Figure 7. Out of plane wrinkle in AtF sample

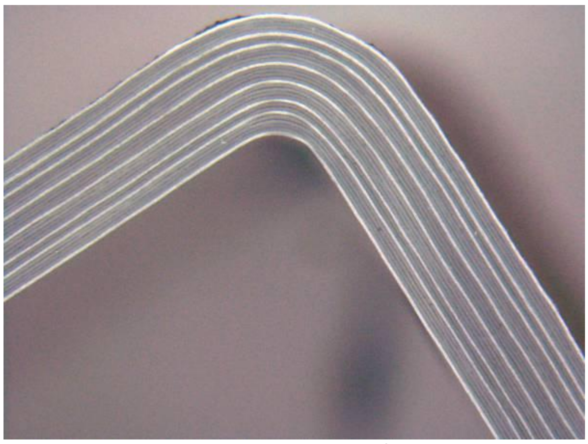

Figure 8. BtF sample (no defect)

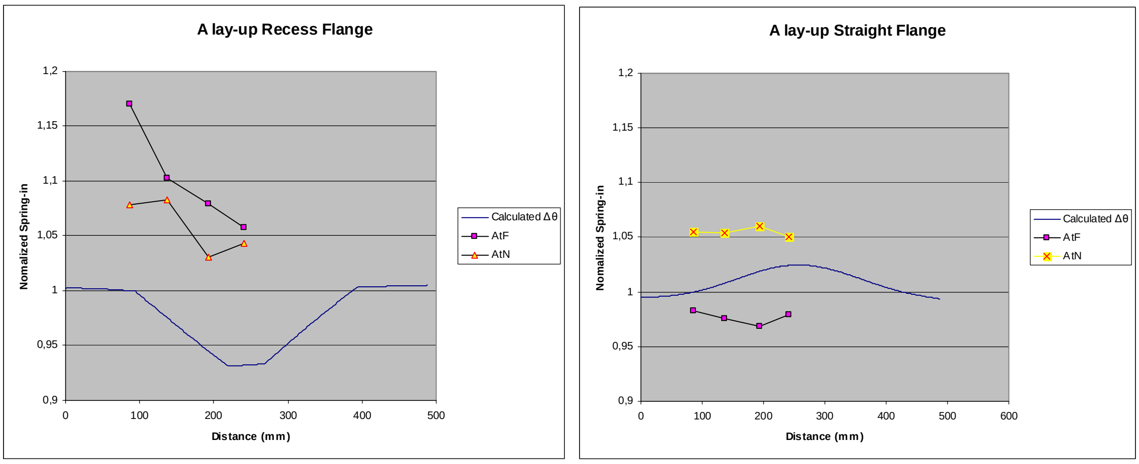

Figure 9. Spring-in A lay-up

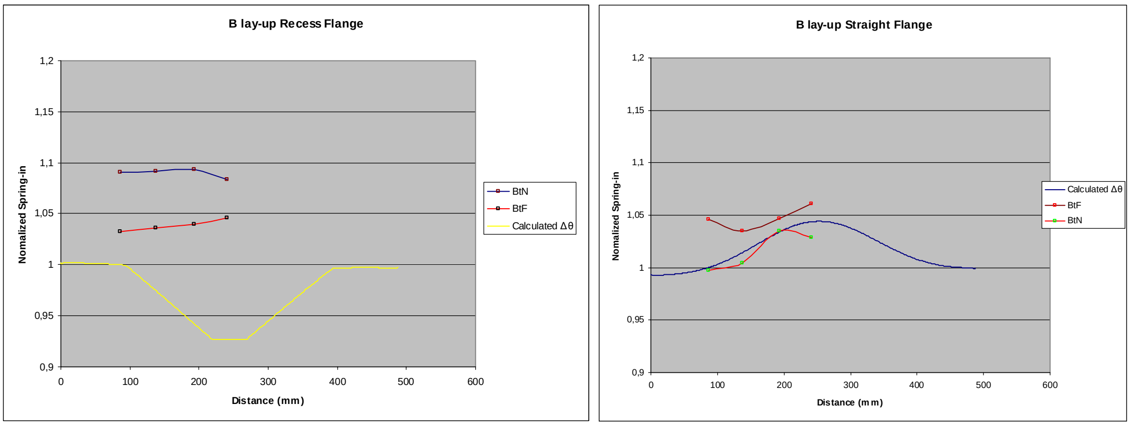

Figure 10. Spring-in B lay-up

5 Discussions

For both the A and the B lay-up there is a remarkable difference in the correlation between the calculated and the experimental spring-in the recess area. A known manufacturing factor that could affect the spring-in is corner thinning (reduction in radius thickness) which for example gives gradients in fiber content. But corner thinning does not explain the spring-in behavior in this case since the thicknesses of the radius were in the range of CPT for all samples, as shown in table 4.

The fiber angles used in the FE-model were determined using a standard draping facility in the soft-ware. The in-built draping facility only takes into account single plies and does not take care of complex forming mechanisms which are depending on coupling effects between the plies. For a straight flange the in-built draping facility gives nearly the real fibre angles but in the recess area the fibre angles are probably not so well predicted. This might give a contribution to the behavior of the spring-in in the recess area.

Due to the difference in lay-up sequence the stiffness difference between A and B lay-up contributes to the spring in with 0.1°. There for the fibre angle deviation from forming could not contribute with stiffness differences in the same level.

The defect in the recess area of the A lay-up could probably affect the spring-in behavior. How ever the difference between the calculated and the experimental spring-in was in the same range for both the A and B lay-up.

The forming gives inbuilt compression for the A lay-up and inbuilt tension for the B lay-up which might give RF compression and RF tension in the cured spars. This will definitely contributes to the spring-in in the recess area.

6 Conclusions

The numerical study show a difference in shape distortion for a quasi-isotropic and a 0° dominated lay-up which is confirmed by the experimental study. The overall correlation for predicted versus experimentally determined spring-in angles are good for the straight flange on a defect free laminate but does not correlate as well for the recess flange. The difference between the calculated and the experimental spring-in, in the recess area, was in the same range for both the spar with wrinkling and the spar without a wrinkling. This underlines the importance of investigating inbuilt fibre stresses from forming.

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