TOWARDS A DESIGN GUIDELINE FOR CORNERS IN COMPOSITE PARTS

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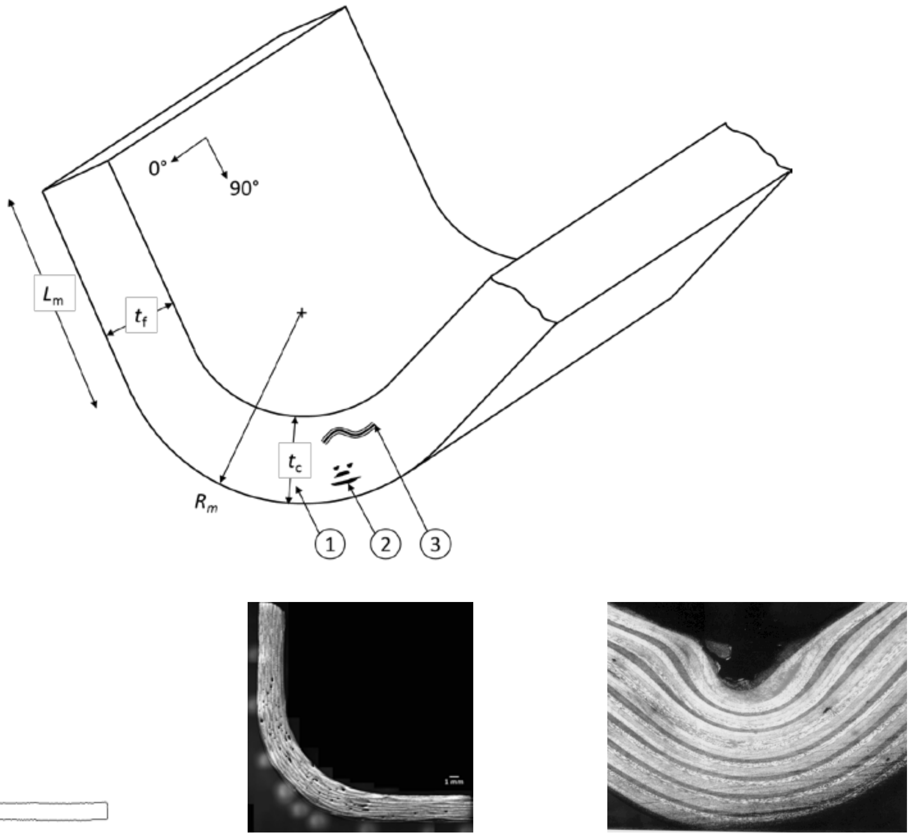
ABSTRACT

The objective of this paper is to propose a new design guideline for corners in composite parts. Particularly the corner thickness deviation depends on the material form, part and tool geometry and processing conditions. The analysis of corner thickness deviation measured on a wide range of materials, geometry and processes revealed that the fraction of [0°] plies influences the magnitude of corner thickening for female tooling. Comparison between a model developed for out-of-autoclave pregregs showed important deviation with the experimental data obtained for autoclave processed unidirectional pregregs. Nevertheless, a practical design development approach is proposed that can be complemented in a structural design tool for the sizing of laminates with corners and their tooling.

1 INTRODUCTION

Manufacturing complex shape laminates will often lead to defects, especially when parts include intricate features such as corners. Over the last thirty years, researchers investigated the typical defects in corners including corner thickness deviation [1, 2], porosity [3, 4] and fibre wrinkling [5, 6]. Figure 1 presents the reference geometrical parameters and represents typical defects found at corners. Most studies, focusing on L-shape laminates, provided a first insight on the defects that may appear in any industrial complex geometry. In corner regions, because of the curvature, the material will undergo a different compaction compared to flat areas. Interply friction might constrain the layers from conforming to the mould, thus preventing an adequate compaction in the corner. Reaction stress is different in the corner and in the flat regions. This leads to a different compaction pressure and a different final thickness in the corner. Thus, depending on the tooling strategy used, corner thinning and thickening can occur for male and female tooling respectively. Common practice in industry is to use simple scaling factors as a function of part thickness to size the tooling radius. Different guidelines exist for male or female tooling, but often they are not based on scientific facts. The objective of this paper is to propose a methodology for the development of design guidelines to minimize defects at corners. The focus of the paper is on corner thickness deviation, which is often indicative of other problems like fibre bridging, wrinkles and porosity.

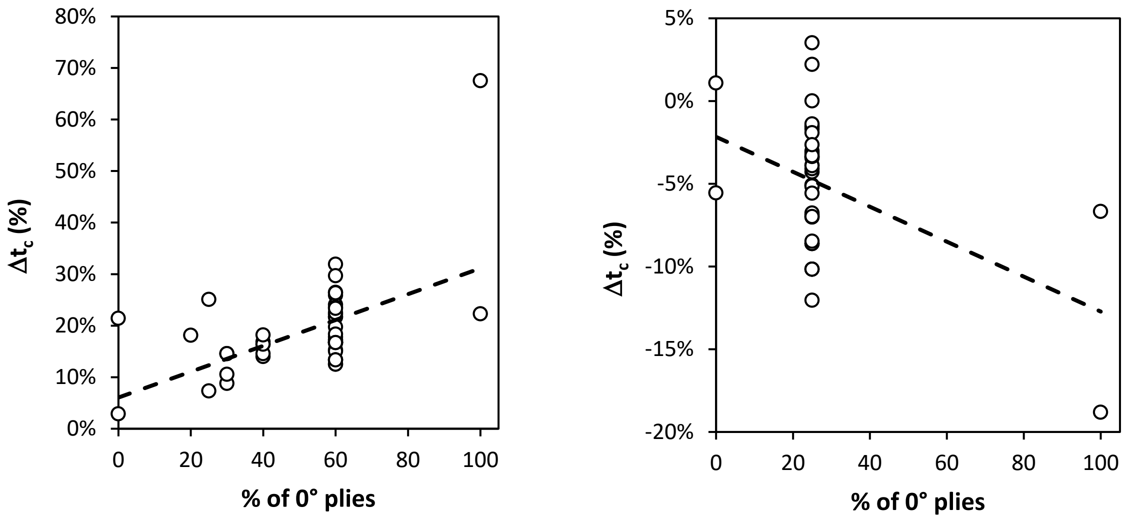


1 2 3

Figure 1: Geometrical representation of corners. Rm is the tool radius, t_f is the nominal flange thickness, t_c is the corner thickness, L_m is the flange length. Typical defects are represented: 1) Thickness deviation, 2) voids and 3) wrinkles. Images taken from [1, 7].

2 CORNER DEVIATION DATABASE

First, data of thickness variation at corners from experiments on L-shape and C-shape laminates with various materials, geometry and processing conditions was analyzed [1, 8-15]. For corners manufactured from unidirectional prepregs, it was found that the percentage of [0°] plies significantly drives the thickness deviation at corners. As shown in Figure 2, the magnitude of corner thickening increases with the percentage of [0°] plies for female tooling (Figure 2a). For male tooling, the magnitude of corner thinning was also proportional to the percentage of [0°] plies, although more data would be required to confirm the trend. Furthermore, the percentage of [0°] plies also drove the occurrence of local corner wrinkling. In general, the processing of corners in out-of-autoclave conditions significantly increased the presence of corner porosity. The higher bulk factor of out-of-autoclave prepregs, particularly with fabrics, caused important corner thickness deviations but few instances of wrinkling.



a) b)

Figure 2: Relative corner thickness deviation Δt_c for unidirectional tape L-shape and C-shape laminates manufactured on a) female tooling and b) male tooling. Corner thinning and thickening corresponds to a negative and positive Δt_c respectively.

3 CORNER DEVIATION MODELLING

A general model was proposed to provide a first approximation of the corner deviation [16]. An empirical rule of mixture was proposed for the relative corner thickness deviation:

$$\Delta t_c = \frac{t_f^c - t_f}{t_f} = g(\Lambda_N) \times \Delta t_c^P + \left(1 - g(\Lambda_N)\right) \times \Delta t_c^F \tag{1}$$

where $g(\Lambda_N)$ is a step function of the conformation number Λ_N defined as $\Lambda_N = R_m/\mu L_m$ where R_m and L_m are defined in Figure 1 and μ is the interply friction coefficient. The step function $g(\Lambda_N)$ depends on material variability, layup operations and other factors. An empirical fitting was proposed with the classical smoothed step function:

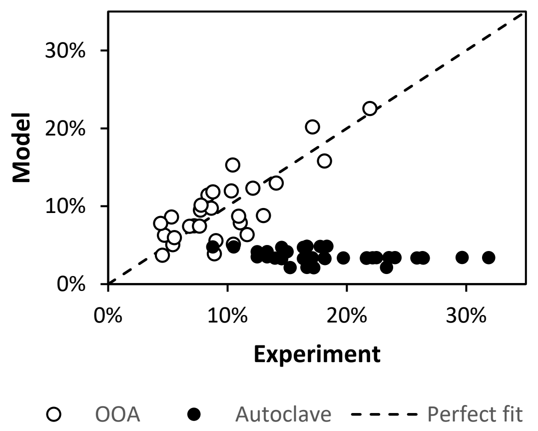
$$g(\Lambda_N) = \frac{1}{2} + \frac{1}{2} tanh\left(\frac{\Lambda_N - a}{b}\right) \tag{2}$$

where a and b are determined experimentally. Typical values are a = 0.0-0.5 for all tools, b = 1.0-1.5 for female tools and b = 1.0-2.0 form male tools. The two extreme cases of friction dominated, Δt_c^F and pressure dominated Δt_c^P corner thickness deviation can be expressed as a function of the laminate and tooling parameters and the prepreg bulk factor, β (Table 1).

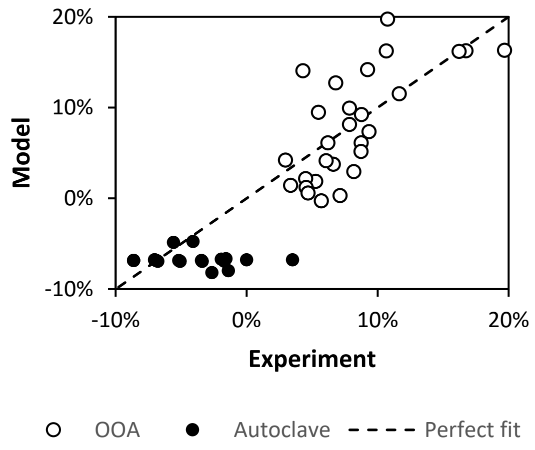
	Friction dominated Δt_c^F	Pressure dominated Δt_c^P
Female tool	$(1-a)\left(\sqrt{2}-1\right)$ where $a = \frac{2-\frac{\pi}{2}\beta}{2-\frac{\pi}{2}}$	$(\beta - 1)\frac{t_f}{R_m}$
Male tool	$\sqrt{2}(a-1) - 1$ where $a = \frac{\beta\left(\frac{\pi}{2}-4\right)+2}{\frac{\pi}{2}-2}$	$-(\beta - 1)\frac{t_f}{R_m}$

Table 1: Equations for the corner thickness deviation computation.

The prediction of corner thickening using Equation (1) was compared to the experimental data for different tooling type and radius, laminate thickness, classes of materials (unidirectional, fabrics) and processing methods (out-of-autoclave, autoclave). The model takes into account the bulk compaction of the prepreg caused by the applied pressure. Values for bulk factor ranges from 1.05 for unidirectional to 1.3 for out-of-autoclave fabrics. Interply shear between the prepreg layers was also considered and ranges from 0.08 for unidirectional to 0.14 for fabrics. The model does not account for intraply shear deformation caused by shear flow [17, 18]. The results indicate that the model captured the trends from experiments when local deformations caused by shear flow were constrained by the fibre architecture. Figure 3 shows that the range of corner thickness deviation measured from experiments for out-of-autoclave prepregs compared well with the model predictions for both female and male tool. On the other hand, the model fails to capture the large corner thickening observed in the experiments for corners processed on a female tool in autoclave. Unidirectional tapes processed in autoclave are more sensitive to shear flow deformation, a mechanism not captured by the model. For male tools, the discrepancy between the experiments and model is not as bad for the autoclave processed corners.



a)

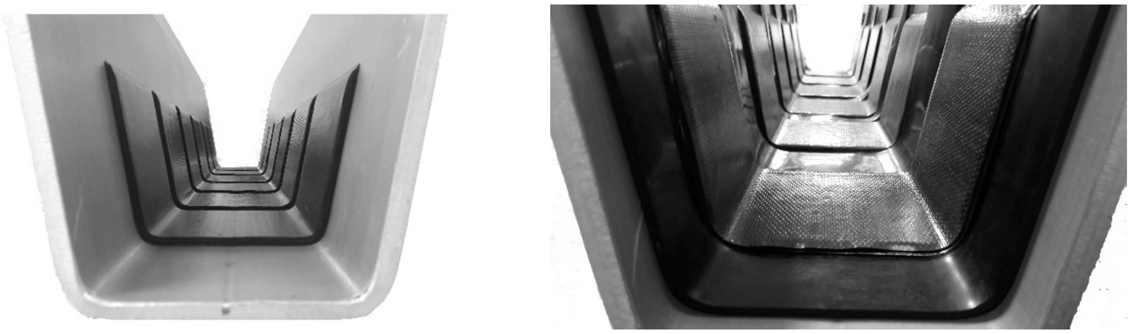


b)

Figure 3: Measured relative corner thickness deviation Δt_c compared to model prediction for out-of-autoclave (OOA) fabric prepreg and autoclave tape prepreg processed on a) female tooling and b) male tooling.

4 CORNER DESIGN GUIDELINE DEVELOPMENT

A set of experiments was designed in order to quantify the contribution of shear flow to corner defect formation. C-shape laminates were manufactured on a female mould and cured in an autoclave. Two sets of experiments were conducted on a 10 mm and 20 mm radius aluminum tool. Six 5.7 mm carbon-epoxy laminates were layup by hand and debulked every 4 plies (Figure 4a). The parts had a width of 100 mm and a flange length of 80 mm. The layup was varied in order to change the percentage of [0°] plies from 0 to 100. The balanced and symmetrical laminates had the following ratio of (0°, ±45°, 90°) plies: (0, 50, 50), (20, 40, 40), (40, 30, 30), (60, 30, 10), (80, 10, 10) and (100, 0, 0). Silicone dams were placed at the edges of the laminates to minimize resin flow and bag bridging as shown in Figure 4b). The parts were cured following the prepreg manufacturer recommended cure cycle in an autoclave with the bag under full vacuum. The laminates profile was measured by scanning cross sections cut across the part width. The relative corner thickness deviation was computed from the maximum measured corner thickness and the average flange thickness.



a) b)

Figure 4: a) C-shape laminates on the tool after debulk. b) Silicone dam arrangement before bagging.

Figure 5 shows the effect of the percentage of [0°] plies on the corner thickening for the 10 mm and 20 mm radius tool. The occurrence of wrinkles for laminates with high percentage of [0°] plies was observed compared to low levels of [0°] plies. The relative corner thickness deviation remains relatively constant below 40% of [0°] plies. At higher levels of percentage of [0°] plies, Δt_c increases exponentially. Finally, the magnitude of the relative corner thickness deviation is lower for larger tooling radius. In light of the experimental observations and the discrepancy between the corner deviation modelling discussed in the previous section, a new design guideline for corner deviation is proposed.

The model presented in Equation (1) was developed for out-of-autoclave prepreg systems where deformation from shear flow can be neglected. The comparison of this modelling approach to experiments performed on tape prepregs cured in autoclave clearly identify the significant effect of the processing conditions, prepreg architecture and shear flow mechanism on the corner thickness deviation. Thus, a corner deviation factor, k, can be determined from the data of Figure 5 and applied to the predicted relative corner thickness as follows:

$$\Delta t_c^* = k\Delta t_c \tag{3}$$

where k is a combination of a factor for the processing condition, k_p and for the effect of the percentage of [0°] plies, k_0:

$$k = k_p k_0 \tag{4}$$

The value for k_p can be obtained from the relative corner deviation of a laminate with 0% of [0°] plies for a given tool radius. In this work, the 10 mm radius tooling was defined as the baseline. Equation (1) was used to compute Δt_c for the tool and laminate design geometry (R_m = 10 mm, L_m = 80 mm and t_f = 5.7 mm). The prepreg bulk factor was obtained from experiments by taking the ratio between the initial and final laminate thickness (β = 1.05) [11]. The friction coefficient was estimated from experiments on typical out-of-autoclave material (μ = 0.08) [19]. The computed relative corner thickness deviation was Δt_c = 0.035 while the measured value was $\Delta t_c(0)$ = 0.161. The processing correction factor was then calculated as:

$$k_p = \frac{\Delta t_c(0)}{\Delta t_c} = 4.57 \tag{5}$$

The value for k_0 was obtained by fitting an empirical relation for the ratio between the measured Δt_c and the predicted value corrected for processing ($\Delta t_c \times k_p$). The following relation for k_0 as a function of the percentage of [0°] plies, f_0 (from 0 to 1), was obtained:

$$k_0 = 1 \qquad f_0 < 0.4 \tag{6}$$

$$k_0 = 1 + 0.004e^{10(f_0 - 0.4)} \quad f_0 \geq 0.4$$

The values of k_p and k_0 where used to predict the relative corner thickness deviation for the 10 mm and 20 mm radius configurations. The results are compared with the experimental data in Figure 6a).

The corrected model fits very well the experimental data, but more importantly, the predictions for the 20 mm radius tooling used one calibration obtained for the baseline 10 mm radius tool. The method was also applied to the dataset presented in Figure 3a) and the result is shown in Figure 6b). The autoclave data points now have better correlation which demonstrate the validity of the proposed method.

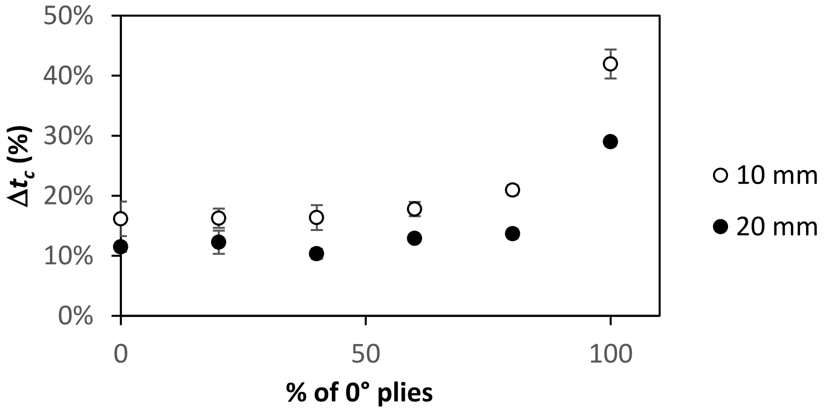


Figure 5: Effect of percentage of [0°] plies on the relative corner thickness deviation Δt_c for unidirectional tape C-shape laminates manufactured female 10 mm and 20 mm radius tooling in autoclave.

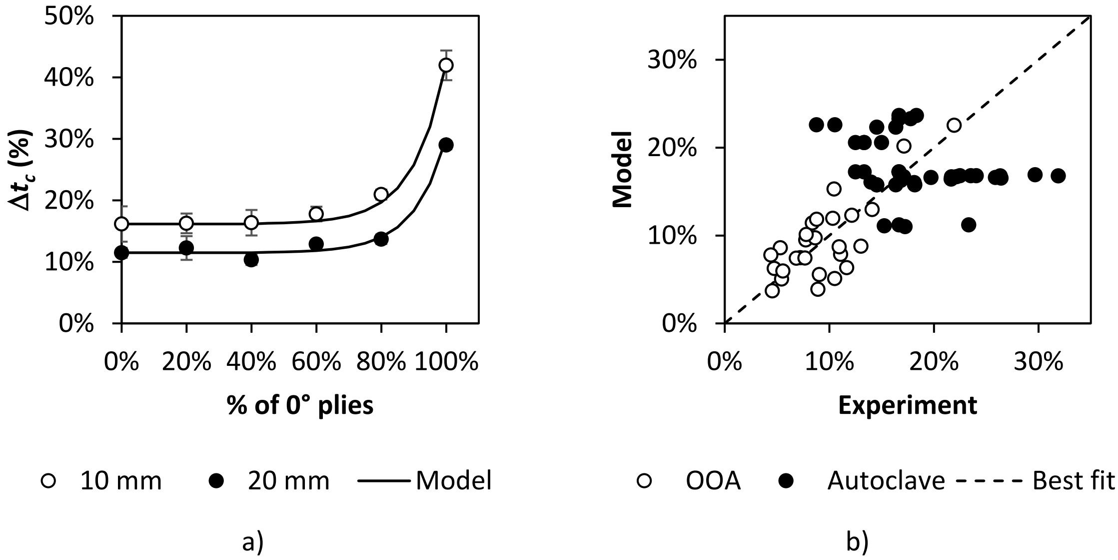


Figure 6: a) Comparison between the predicted (Equation (3)) and measured relative corner thickness deviation for corner laminates processed on a female tooling in autoclave. b) Measured relative corner thickness deviation Δt_c compared to model prediction for out-of-autoclave (OOA) fabric prepreg (Equation (1) and autoclave tape prepreg (Equation (3)) processed on female tooling.

5 CONCLUSIONS

In this paper, the analysis of a large database of experiments on laminate corner thickness deviation showed that:

- The percentage of [0°] plies increases the magnitude of corner deviation particularly above 40%
- A corner compaction model previously developed for out-of-autoclave prepreg cannot capture the magnitude of corner thickening caused by autoclave pressure or excessive shear flow of the [0°] plies.

A new practical design guideline was proposed for tooling and laminate design at corners.

For female tooling

1. For Out-of-autoclave conditions set $k_p = k_0 = 1$ and go to Step 3
2. For Autoclave conditions with unidirectional prepreg
   2.1. Select a baseline tool radius, laminate thickness and flange length
   2.2. Manufacture a minimum of three laminates with 0, 60 and 100 of [0°] plies
   2.3. Measure the relative corner thickness deviation $\Delta t_c(f_0)$ as a function of the percentage of [0°] plies
   2.4. Use Equation (1) to compute Δt_c for the baseline conditions in Step 2.1
   2.5. Compute the processing correction factor: $k_p = \Delta t_c(0)/\Delta t_c$
   2.6. Fit the function $k_0 = 1 + \mathrm{a}e^{b(f_0-0.4)}$ for data at $f_0 \geq 0.4$
3. Use the Equations (1), (3) and (4) to compute the corrected relative corner thickness deviation

For male tooling

1. Set $k_p = k_0 = 1$
2. Use the Equations (1), (3) and (4) to compute the corrected relative corner thickness deviation

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