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The Influence of the Sample Size of Bias Extension Tests on the Results of Forming Simulations of Fiber-Reinforced Thermoplastics

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Abstract. This work presents a sensitivity analyzes of the influence of deviations in the shear stress vs. shear angle curves of bias extension tests of fiber-reinforced thermoplastics on the results of forming simulations. The investigations are carried out on the basis of a double dome benchmark geometry from the Ford Motor Company. Its experimental results of shear angle values and wrinkling are compared to the simulation results. The initial values for sensitivity analyzes are the shear stress-shear angle curves determined within further preliminary investigations on the basis of different sample sizes and cutting directions. Then these are gradually scaled. Finally, it will be discussed which deviations in the shear stress-shear angle curve are permissible in order to achieve a maximum deviation of 20% between simulation results and the real part. This is assumed to be the target value for this study.

Introduction

FE forming analysis of fiber reinforced thermoplastics (frt) are used to predict the formation of wrinkles and fiber orientation of the formed component during process development. Several material tests are necessary for validation of FE models to determine the different stiffness values for tensile, compression, bending and fabric shear. Latter has the greatest influence onto the FE forming results [1]. The bias extension test is often used for the characterization of shear stress vs. shear angle curves. There is no standardization regarding the sample size, but various authors explain, that this value should be at least or greater than 2 [2].

The initial values for sensitivity analyzes are the results of preliminary investigations of the bias extension test on the basis of different sample sizes and cutting directions [3]. It has been shown that the use of different sample sizes can lead to different results of the determined shear stress vs. shear angle curve.

In this study, the influence of these shear stress vs. shear angle curves on the simulation results of the forming process of a double dome geometry is examined. FE results are compared to the experimental results of a real part that is formed within a prior study introduced by Graef et al. [4]. In this work, a maximum deviation of 20% between the simulation results and the real component is aimed for.

The investigated material is Tepex dynalite 102- RG600(x) from BondLaminates with glass twill fabric and polyamide 6.

DoubleDome Forming Study

The double dome forming study and the measurement of shear angle and wrinkling has been introduced by Graef et al. [4]. There is no blank holder in order to allow wrinkling. The comparative values used in this study are described below. The temperature of the blank is about 260 ° C after the transfer into the tool, shortly before the punch is getting into contact to the blank. Figure 1 shows a double dome part and its positions (1-4) for shear angle measurement and cutting lines (dashed) for wrinkling measurement. Figure 2 shows the results for the ten highest shear angle values for position

1 and 4 in descending order. Positions 1 and 3 have negative shear angle values and positions 2 and 4 have positive shear angle values according to Figure 3.

The wrinkling behavior along a cutting line (Fig. 1) is shown in figure 4. There are two significant wrinkles at the outside of the blank. Their height (h) and the distance (d) between them are measured.

The comparative values for the simulation results are as follows:

Max. Shear angle:	**Wrinkling:**
$\varphi_{pos.}$= 45,7° $\varphi_{neg.}$= 39,3°	h_2= 73 mm h_3= 73,5 mm d= 182 mm

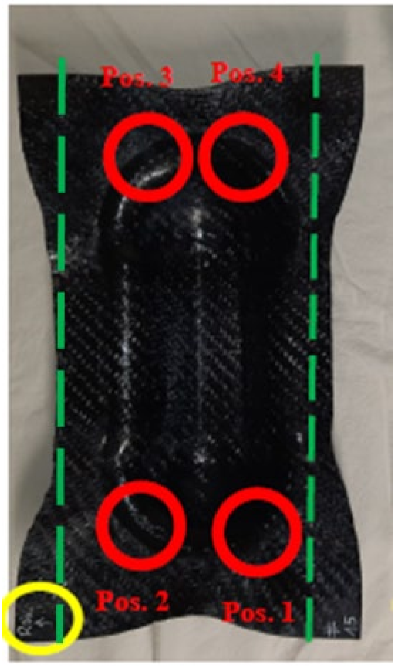

Figure 1: DoubleDome part: cutting lines and positions with max. shear angles [4]

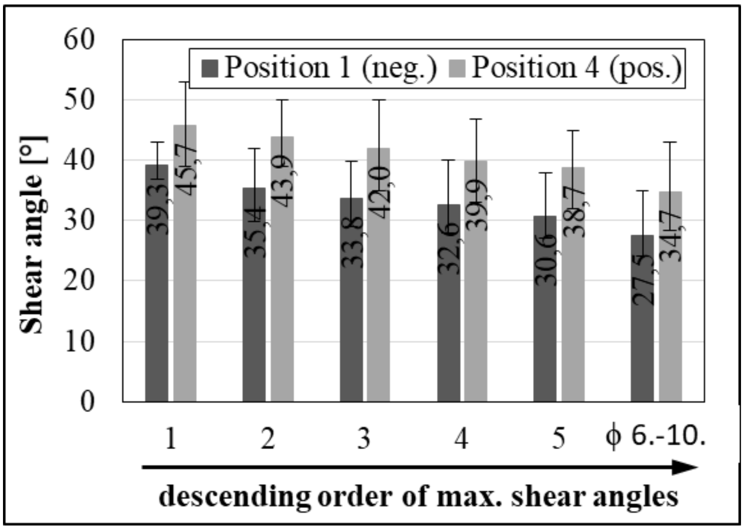

Figure 2: Highest shear angles values for position 1 and 4 of double dome part (T=260°C)

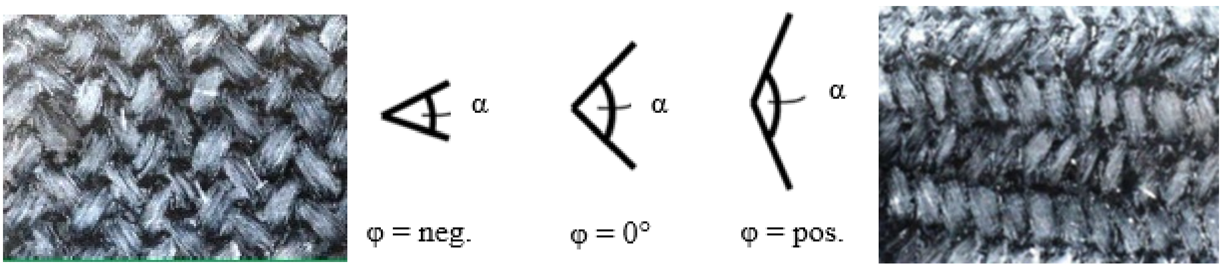

Figure 3: Positive and negative direction of fabric shear (shear angle – φ)

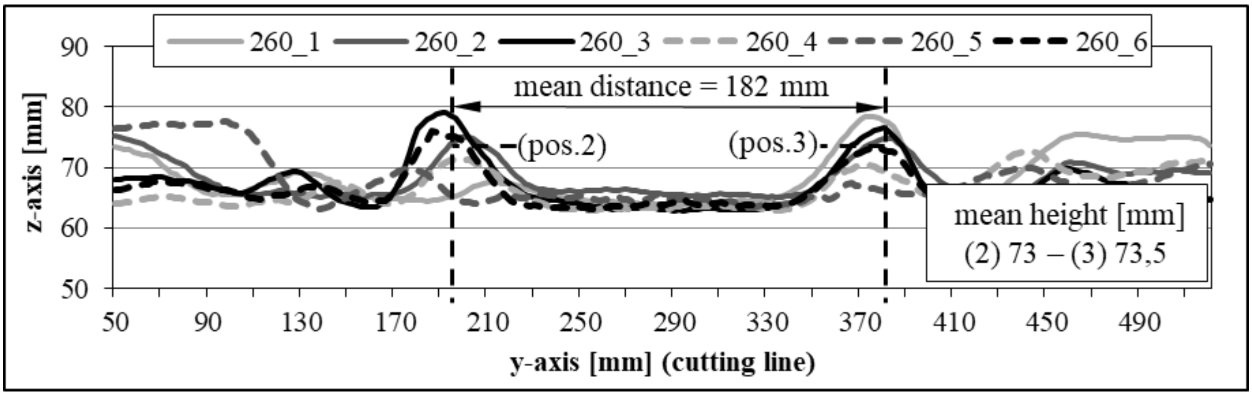

Figure 4: Sectional view of the DoubleDome wrinkling (260°C)

DoubleDome Forming Simulation

The forming simulations are performed with Abaqus/ Explicit. The FE model in this work bases on the unit cell and a checkerboard mesh (Chck) introduced in prior studies [5, 6, 7]. It consists of membrane elements with *Fabric material card of Abaqus for in-plane properties (tensile, compression, fabric shear) and beam elements to represent the out-of- plane bending behavior.

Material input data. The *tensile modulus* has been determined within tensile tests at 220°C. Cap strips are glued to the ends of the sample in order to apply the tensile forces evenly to the sample. The adhesive connection fails above the melting temperature of the matrix material. Thus, the high tensile forces could not be transferred to the sample.

The *compressive stiffness* is assumed to be about 20% of the tensile stiffness. This assumption is based on the investigations of Nishi et al. [8]. The authors determined the different stiffness values for plain weave fabrics with a meso-scale FE model.

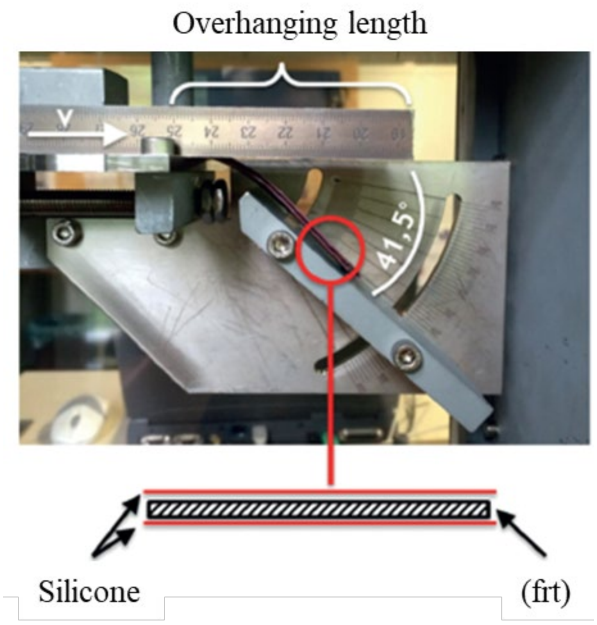

Figure 5: Cantilever bending test [8]

The *bending stiffness* has been determined within a cantilever bending test introduced by Engel und Graef [9]. Figure 5 shows the test setup. A rectangular specimen is pushed over an inclined plane with an angle of 41.5° at a constant velocity until its free edge hits the surface of the plane. The overhanging length l_o is measured with a scale. The bending stiffness can be calculated according to Eq. 1 and Eq. 3 [10]. The beam elements of the unit cell within FE model have an elastic isotropic material model. To take into account the bending stiffness of the frt, the elastic modulus has been calculated with Eq.3 and a second moment of area (I) for a circular cross-section of the beam elements.

$$B = F_1 * \left(\frac{l_o}{2}\right)^3. \tag{1}$$

$$F_1 = g_n * \frac{m}{l}. \tag{2}$$

$$E = \frac{B}{I}. \tag{3}$$

Table 1: Nomenclature for Eq. 1-3

Bending stiffness	B	$[N*mm^2]$		Gravity	g_n	$\left[\frac{mm}{s^2}\right]$
Linear weight force	F_1	$\left[\frac{N}{mm}\right]$		Mass	m	[kg]
Overhanging length	l_o	[mm]		Sample length	l	[mm]
Young´s Modulus	E	$\left[\frac{N}{mm^2}\right]$		Second Moment of Area	I	$[mm^4]$

The *shear behavior* has been analyzed within bias extension tests. The initial values for sensitivity analyzes in this work are shown in figure 6. The tests have been performed at 260 °C and a velocity of 200 mm/min. The proportions of the bias extension test samples are listed in table 2. These are scaled by the factors 0.5, 1 and 2 for FE sensitivity study in order to analyze the influence of different shear stress values.

Figure 6 shows different shear stress vs. shear angle curves for different height to width ratios (H/W) and for positive and negative directions of fabric shear, that is shown exemplary for H/W=3.

Table 2: Sample proportions and scaling factors for FE sensitivity study

Proportion $\left(\frac{H}{W}\right)$	Height (H) [mm]	Width (W) [mm]		Scaling factor
2	160	80		1, 0.5, 2
2.5	150	60		1
3	150	50		1, 0.5, 2

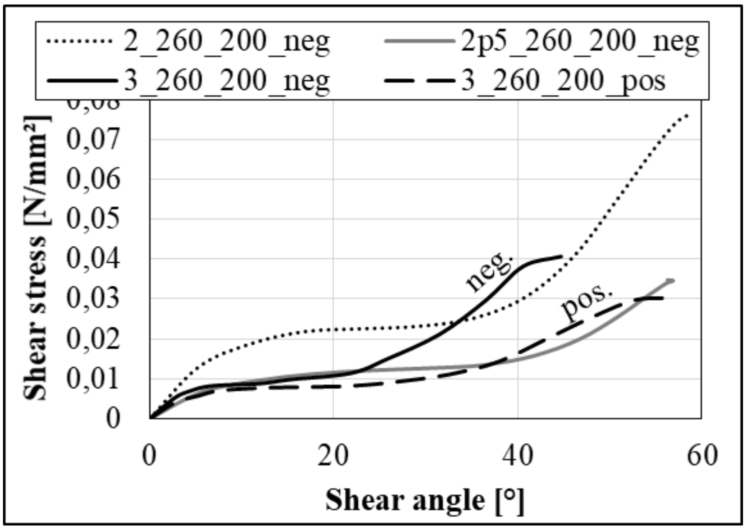

Figure 6: Bias extension test with different sample proportions and shear directions (pos./neg.) for glass twill/ PA6 [3]

The specimen with H/W = 2 has about twice the shear stress values as the specimens with H/W = 2.5 and 3. Their shear stress values are nearly the same up to a shear angle of about 20°. Afterwards, the significant increase in shear stress is shifted to higher shear angles for the specimens with H/W = 2.5 compared to H/W = 3. This behavior is also shown by Cao et al. [11] and Lee et al. [12] for a dry twill weave with a constant specimen's length of 300 mm.

Furthermore, increasing width results in lower shear stress values if H/W is constant [11, 12, 13]. Cao et al. [11] also show the lowest shear stress values for H/W = 2.5 and the highest values for H/W = 2 for plain weave when comparing different specimens with constant width. Fabric shear stops, when the fibers are in the direction of the load or the shear angle reaches a maximum value, the locking angle [14]. This value also differs for several specimen sizes and proportions.

Results

Table 3 shows the results of the FE sensitivity study of the forming process of the double dome part. The deviations between the comparative values of maximum shear angles, height and distance of the real part and FE results are given as a percentage. First, the FE results with shear test data from bias extension tests (scaling factor 1) are listed. The best FE results are reached with the shear test data of H/W = 3 (Fig. 7). H/W= 2.5 also has a deviation below 10% to experimental results. The results with shear test data of H/W=2 as well as the results of a scaling factor of 2 don't reach the aim of a maximum deviation of 20%. Positions 1 to 4 (Fig. 1) show significant wrinkling (Fig. 8).

Reducing the shear stress values of FE input data with a scaling factor of 0.5 leads to a better agreement between FE results and experimental results. H/W= 2 has better maximum shear angle results, and H/W=3 has better wrinkling results. Their shear data have different locking angles.

According to Figure 6 and the results investigated by Cao et al. [11] and Lee et al. [12] minimum shear stress values should be reached with a height to width ratio of H/W = 2.5 and a large sample width. This relationship as well as the influence of specimen's size onto the locking angle will be validated within experimental bias extension tests in future studies.

Table 3: Comparison between FE results and experimental results of double dome part

simulation results			max. shear angles [°]				Height (wrinkles) [mm]				distance (wrinkles) [mm]	
H/W	Factor	Result	neg.	[%]	pos.	[%]	Pos. 2 (+)	[%]	Pos. 3 (-)	[%]		deviation [%]
3	1	✓	37,5	4,7	48,5	6,1	79,0	8,2	80,7	9,8	166,0	8,8
2	1	×	-	-	-	-	78,7	7,8	79,2	7,8	147,0	19,2
2,5	1	✓	35,5	9,8	49,6	8,6	79,6	9,0	79,1	7,6	164,0	9,9
3	2	×	-	-	-	-	77,5	6,2	76,9	4,6	140,0	23,1
3	0,5	✓	37,7	4,0	47,2	3,4	75,1	2,9	73,3	0,3	175,4	3,6
2	2	×	-	-	-	-	78,3	7,3	83,5	13,6	164,1	9,8
2	0,5	✓	39,4	0,2	45,4	0,7	80,4	10,1	79,4	8,0	170,9	6,1
experimental results			39,3		45,7		73		73,5		182	

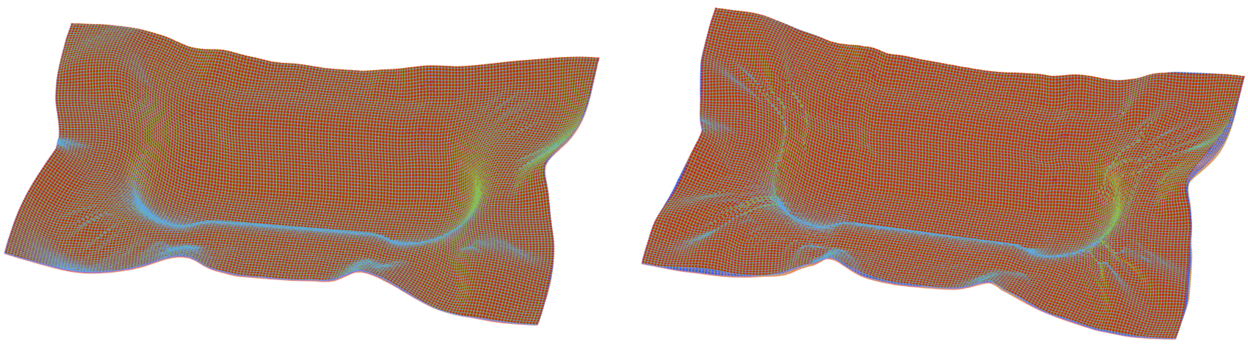

Figure 7: FE results of DoubleDome part: H/W = 3 (left); H/W= 2 (right)

Summary

In this study, the influence of shear stress vs. shear angle curves of bias extension tests of fiber reinforced thermoplastics on the simulation results of the forming process of a double dome geometry is examined. The use of different sample sizes within bias extension tests leads to different results of the determined shear stress vs. shear angle curve. FE results are compared to the experimental results of a real part. The lowest shear stress curves reach the best agreements. This should be passed by a height to width ratio H/W of 2.5 for bias extension test specimen and a large sample width. This conclusion will be validated within experimental bias extension tests in future work.

Acknowledgements

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