IN-PLANE SHEAR DEFORMABILITY OF OUT-OF-AUTOCLAVE PREPREGS UNDER DOUBLE-DIAPHRAGM VACUUM COMPACTION

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Abstract

During the diaphragm forming process for carbon / epoxy prepregs, a vacuum seal is applied between the upper and lower diaphragms to compact and hold the laminate. Therefore, a thorough characterization of the in-plane shear behavior of fabrics under diaphragm forming conditions must take into account the effect of vacuum-sealing and compaction between the two diaphragms during bias extension. The study presented here examined the shear angles of out-of-autoclave 8-harness satin woven carbon / epoxy prepregs under diaphragm compaction. A bias extension test was conducted to study the effect of diaphragm compaction and ply interactions on shear properties. The test was performed at different compaction levels, and changes in shear angle with respect to vacuum levels and diaphragm compaction forces were observed. The contribution of diaphragm material and ply interaction to shear stiffness was evaluated and compared with results from a direct bias extension test. The samples were tested at both room temperature and at elevated temperatures using a radiant heater. The results show that shear angle decreases significantly as vacuum pressure and compaction is applied between the two diaphragms. This finding indicates that vacuum levels and compaction forces have a significant influence on the deformation limit and wrinkling onset during the diaphragm forming process.

1. Introduction

Conventional composite manufacturing techniques, such as hand lay-up, are labor intensive, costly and efficient only for small production runs. In order to automate the composite manufacturing techniques and reduce processing costs for the aerospace industry, alternative approaches, such as the resin-transfer molding, stamping, and diaphragm-formation processes, have been developed.

Double-diaphragm forming, which was initially applied to thermoplastic matrix composites, is one of the most important sheet-forming processes for composite materials. A typical double-diaphragm forming process consists of three steps [1, 2]. A flat laminate must first be placed between two deformable sheets known as diaphragms, which are themselves clamped over a forming box. The space between the diaphragms is subjected to a full vacuum seal. Next, the laminate between the diaphragms is heated up to processing temperature. Finally, controlled vacuum pressure applied to the forming-box cavity below the lower diaphragm causes forming to take place. Polymeric diaphragms are commonly used due to their ability to deform without rupturing under high processing temperatures [3, 4].

In-plane shear deformation is the dominant deformation mechanism used during formation of double-curved parts [5]. This deformation mechanism affects woven fabrics, warping the rotation of the yarns at their crossovers and causing a change in fiber orientation. Rotation around weave crossover is mainly limited by the ability of fiber yarns to contact each other (known as “locking angle”; see [6, 7]. A critical locking angle is reached when all yarns come into contact with each other and become compressed, causing a rapid increase in force that results in wrinkling [8]. Simulations conducted in [1, 2] confirm the necessity of scaling up the in-plane shearing stiffness from what was measured in bias extension tests without compaction pressures in order to properly test this phenomenon. The present study implements compaction between two diaphragms during the bias extension test in order to understand the relative magnitude of in-plane shear stiffness under diaphragm forming conditions; these results can then be incorporated into bias extension test simulations.

The purpose of this study is to evaluate the magnitude of in-plane shear stiffness and shear angles under double-diaphragm vacuum compaction using a bias extension test. Changes in shear angle with respect to applied compaction forces are observed. In addition, the contribution of diaphragm compaction to shear stiffness is measured by comparing the results of the compaction test with results from a direct bias extension test.

2. Experiment

2.1. Materials

The out-of-autoclave prepreg selected for this study was the 8-harness satin woven carbon/epoxy from Cytec Engineered Materials. The resin code is (Cycom 5320) toughened epoxy and the fabric has 3K fibers per tow. The fabric areal weight is 375 g / m^2 and the resin content is 36 % by weight. The measured thickness of uncured one-ply is approximately 0.47 mm. The diaphragm material used in this study was a translucent silicone rubber (EL1040T) manufactured by Torr Technologies Inc. (thickness 1.6 mm).

2.2. Bias extension test under diaphragms compaction

A bias extension test was conducted to study in-plane shear deformation under diaphragm forming compaction. Prepreg samples were placed between two diaphragm films; compaction was generated using a sealed vacuum bag due to the difficulty of sealing the two diaphragms together. **Figure 1** illustrates in detail the attachment of the prepreg sample and diaphragm films to the custom grips. The bias extension setup clamped in the tensile machine is shown in its entirety in **Figure 2**. The load needed to extend the prepreg sample under diaphragm compaction can be described by the following formula [9]:

$$F_s = F_t - F_d - F_f. \tag{1}$$

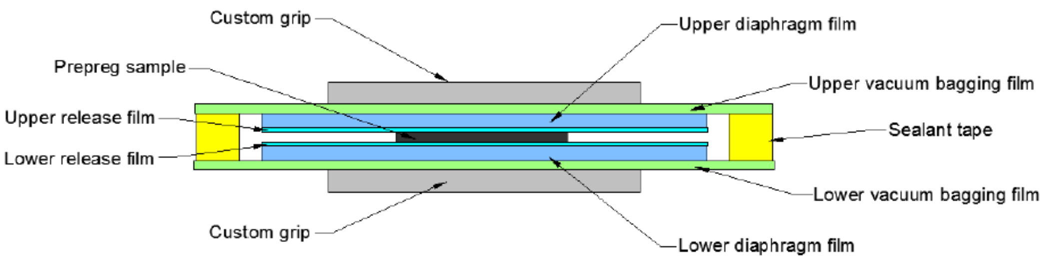

Figure 1. Detailed diagram of attachment of prepreg sample and diaphragm films to the customs grips.

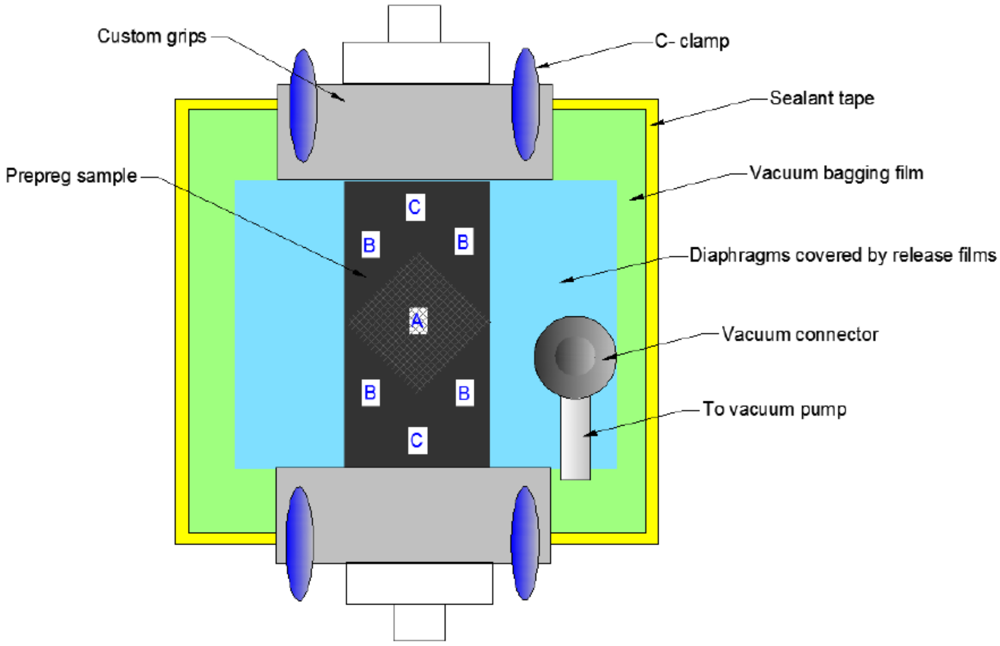

Figure 2. Bias extension setup under diaphragm forming compaction.

In this equation, F_s is the load needed to extend the prepreg sample, F_t is the total measured load of the bias extension setup with the prepreg sample, F_d is the load required to extend the bias extension setup without the prepreg sample, and F_f is the friction force between the sample and diaphragm films. The test conditions of this case are presented in **Table 1**.

Table 1. Test conditions of bias extension under compaction.

Temperature, °C	Cross-head rates, mm/min	Number of layers, ±45°	Level of compaction, kPa
RT	20	2	100, 50, 20
50	20	2	100
90	20	2	100

3. Results and discussion

Bias extension samples were taken in a 50 °C environment under 100 kPa of compaction in order to study the effect of diaphragm forming compaction on in-plane shear deformation, with the goal of applying these findings to future diaphragm forming simulations. In order to determine the magnitude of each load at each displacement, the bias extension setup was tested twice, once with the prepreg sample and once without it. The orange dashed line in **Figure 3** represents the total measured load of the bias extension setup with the prepreg sample (F_t); the onset of sample buckling corresponds to the large deformation point (between 20 to 25 mm). The load required to extend the bias extension setup without the prepreg sample (F_d) is shown by the blue dashed line in **Figure 3**. Note that, in this case, no buckling is observed at the large deformation point. The load needed to extend the prepreg sample (F_s) was calculated according to equation (1); the results are illustrated by the black diamonds in **Figure 3**. The magnitude of the load response gives a good indication of the actual load needed to elongate the prepreg samples. However, slight differences in the magnitude of the load needed to extend the prepreg sample were found among all test trials. This difference is attributed to a loss of compaction in the prepreg sample during testing.

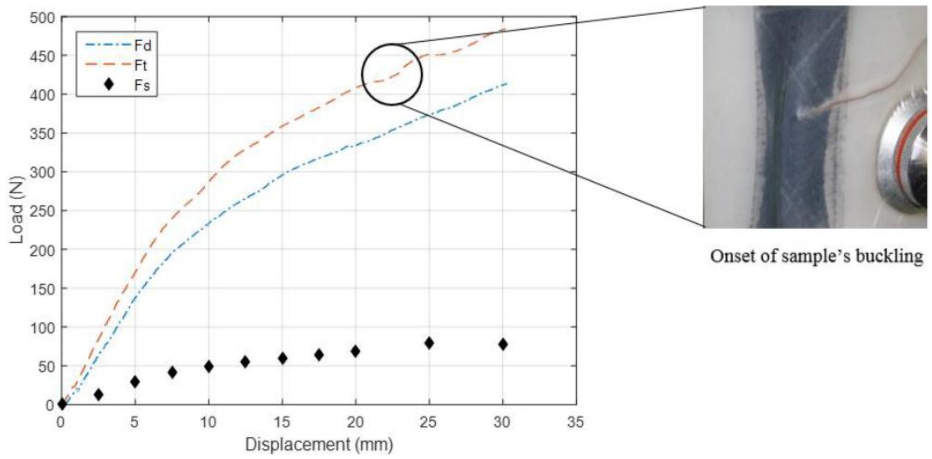

Figure 3. Load-displacement response to the bias extension test under 100 kPa compaction at 50 °C. F_s indicates the load needed to extend the prepreg sample; F_t is the total measured load of the bias extension setup with the prepreg sample; F_d is the load required to extend the bias extension setup without the prepreg sample.

3.1. Change in shear angle

The change in shear angle can be measured by analyzing the series of test images taken by the digital cameras during the study with AutoCAD. A comparison of the measured angle found during the compaction test and the angle found during the direct bias extension test is shown in **Figures 4** and **5**. The results show that the shear angles decreased significantly in the bias extension test with compaction. Therefore, it appears that the compaction parameter applied during double-diaphragm forming successfully restricted the in-plane shear deformation. Note, however, that the laminate must be in a flat and tense state at the onset of the procedure to avoid any compression that may lead to wrinkling during the forming step. Controlling this factor during the initial forming step is therefore essential in order to avoid a compressive state and to reach a higher degree of deformability. A detailed comparison between the direct bias extension test and the bias extension test under 100 kPa compaction for both temperatures is summarized in **Table 2**. It can be seen that the load needed to extend the prepreg sample in the direct bias test was very low compared with the load needed in the compaction test. On the other hand, the shear angles measured during the compaction test were significantly smaller than those measured during the direct bias test.

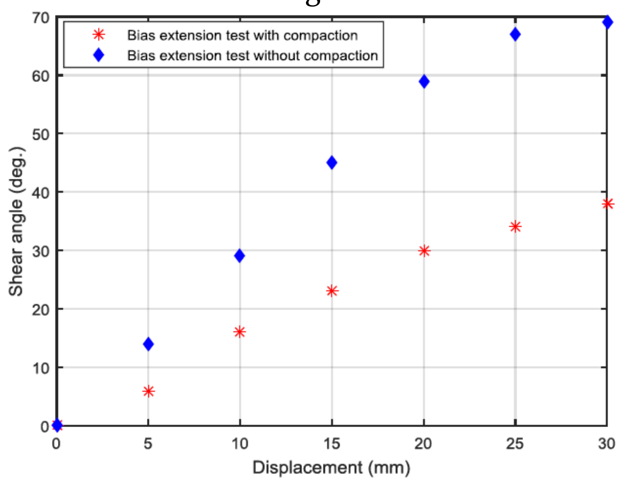

Figure 4. Comparison between measured shear angle using direct bias extension test and measured shear angle using bias extension test with 100 kPa compaction, both at 50 °C.

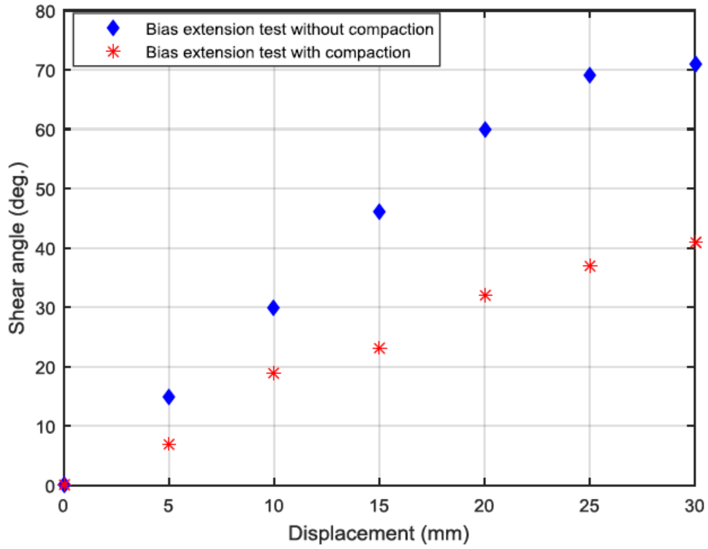

Figure 5. Comparison between measured shear angle using direct bias extension test and measured shear angle using bias extension test with 100 kPa compaction, both at 90 °C.

Table 2. Comparision between direct bias test and bias under 100 kPa compaction.

	50 °C				90 °C			
	Direct bias test		Bias test under 100 kPa		Direct bias test		Bias test under 100 kPa	
Displacement (mm)	Load (N)	Shear angle (deg.)	Load Fs (N)	Shear angle (deg.)	Load (N)	Shear angle (deg.)	Load Fs (N)	Shear angle (deg.)
5	1.462718	14	29.32702	6	0.389929	14	21.355	7
10	1.716431	29	49.05017	16	0.902454	31	45.5031	19
15	4.068002	45	60.1025	23	1.862866	46	52.9534	23
20	13.42035	59	68.148	30	3.698215	62	59.3367	32
25	35.78173	67	80.2394	34	8.361	69	69.5943	37
30	66.72067	69	78.9854	38	9.36147	70	72.8692	41

3.2. Influence of compaction level

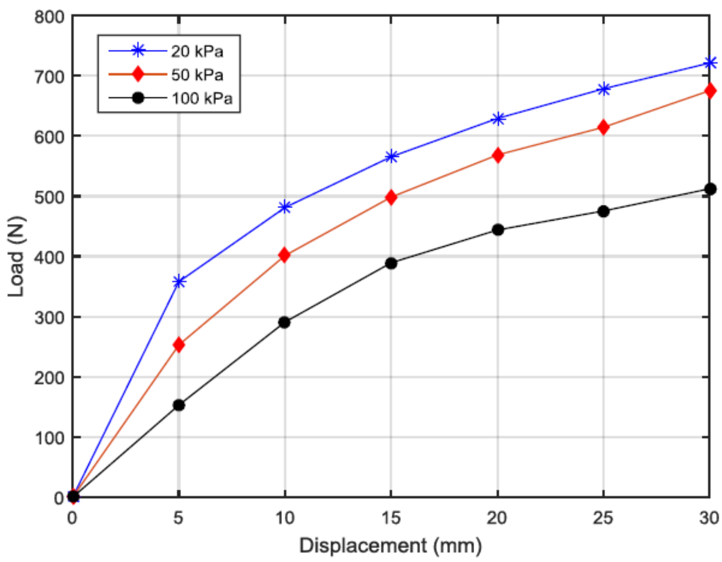

Figure 6. The effect of compaction level on the load response.

The goal of the compaction procedure carried out during the bias extension test in this study was to simulate the vacuum applied between double diaphragms during the forming process. The effect of this vacuum parameter was investigated at three compaction levels: 20, 50 and 100 kPa, as shown in **Figure 6**. An unexpected correlation was observed between compaction level and load response: as the level of vacuum compaction increased, the load decreased at each selected displacement. For instance, the load measured at 15 mm displacement and 50 kPa was around 498 N, while a load of 573 N was measured at the same displacement with 20 kPa. However, further investigation is necessary to confirm this phenomenon and arrive at reproducible data.

4. Conclusion

A new bias extension test was evaluated under vacuum compaction at different temperatures and compaction levels. The results show that shear angle decreases significantly as vacuum pressure, and therefore compaction, is applied between two diaphragms. This finding indicates that compaction force has a significant influence on the deformation limit and wrinkling onset during the diaphragm forming process; thus, compaction should be taken into appropriate consideration in future simulations. It was found that the load required to extend a prepreg sample during a direct bias test is very low compare to the load required during the bias test under compaction. On the other hand, the shear angles produced during the bias test under compaction were significantly smaller. In addition, load response was found to increase as vacuum compaction level decreased. However, further investigation is necessary to confirm this phenomenon and arrive at reproducible data.

Acknowledgements

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