256 shades of gray

Application of image processing to evaluate the effect of sample geometry and constant shear strain rates in the picture-frame test

Krogh, Christian; Dangora, Lisa M.; White, Kari D.; Jakobsen, Johnny; Sherwood, James A.

Published in:
Proceedings of the 22nd International ESAFORM Conference on Material Forming, ESAFORM 2019

DOI (link to publication from Publisher):
10.1063/1.5112506

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Krogh, C., Dangora, L. M., White, K. D., Jakobsen, J., & Sherwood, J. A. (2019). 256 shades of gray: Application of image processing to evaluate the effect of sample geometry and constant shear strain rates in the picture-frame test. In P. Arrazola, E. Saenz de Argandona, N. Otegi, J. Mendiguren, M. Saez de Buruaga, A. Madariaga, & L. Galdos (Eds.), *Proceedings of the 22nd International ESAFORM Conference on Material Forming, ESAFORM 2019* Article 020001 AIP Publishing (American Institute of Physics). https://doi.org/10.1063/1.5112506

256 shades of gray: Application of image processing to evaluate the effect of sample geometry and constant shear strain rates in the picture-frame test

Cite as: AIP Conference Proceedings **2113**, 020001 (2019); https://doi.org/10.1063/1.5112506

Christian Krogh, Lisa M. Dangora, Kari D. White, Johnny Jakobsen, and James A. Sherwood

256 Shades of Gray: Application of Image Processing to Evaluate the Effect of Sample Geometry and Constant Shear Strain Rates in the Picture-Frame Test

Christian Krogh[1,a)], Lisa M. Dangora[2], Kari D. White[2], Johnny Jakobsen[1] and James A. Sherwood[2,b)]

[1] *Department of Materials and Production, Aalborg University, Fibigerstraede 16, 9220 Aalborg East, Denmark.*
[2] *Department of Mechanical Engineering, University of Massachusetts, Lowell, One University Ave., 01854, Lowell, MA, USA.*

[a)] Corresponding author: ck@mp.aau.dk
[b)] James_Sherwood@uml.edu

Abstract. Shearing or trellising is recognized as the primary deformation mechanism in textile-reinforced composite forming processes. A popular method for characterization of the shear properties of a ply is the picture-frame test. The test setup involves the clamping of a cruciform shaped specimen in a frame hinged at its corners. During the processing of the test results, it is often assumed that the shear distribution in the central square of the sample is uniform, such that a shear force vs. shear angle relation can be calculated based on kinematics. One thing to note is that a constant displacement rate of the frame yields a nonlinear shear-strain rate throughout the test. Relying on Digital Image Correlation (DIC), this study considers two concepts in relation to the picture-frame test: First, the effect of sample geometry is tested, i.e. whether modifications of the standard cruciform shape influence the uniformness of the shear-strain field. Two different materials are considered: a woven carbon-fiber prepreg and a thermoplastic cross-ply sheet. Second, methods of obtaining constant shear rate data are explored. The methods involve programming of a universal testing machine with a multi-linear approximation of a nonlinear crosshead displacement rate and post-processing data obtained with a constant crosshead rate.

INTRODUCTION

The use of composites in industry is increasing and new ways of applications constantly emerge. An essential prerequisite for a successful application of composites is a thorough understanding of a given material system's mechanical properties and in particular shearing in the uncured/unconsolidated state as it governs the forming behavior [1].

Several researchers have successfully applied the *picture-frame test* to characterize the shear behavior of unconsolidated composite materials [2, 3, 4]. Some issues with the test have been identified, including the sample geometry. Because of the frame design with joints and clamping area, the sample geometry takes the shape of a cruciform, but the gage area is only considered to be the central square of the sample. Thus, the "arms" could influence the measurements in the gage area. For reinforcement materials without matrix, some researchers have adopted a technique of removing the transverse fibers from the arms [2, 5]. However, for materials systems with the matrix integrated, the transverse fibers are not so easily removed.

In this study, the effect of sample geometry is investigated for two different material systems, namely a woven carbon-fiber prepreg and a thermoplastic cross-ply sheet. The standard cruciform shape of the picture frame test is modified in two ways: by cutting slits and by dissolving the resin in the arms to evaluate its effect on the uniformness of the shear strain field. Next, methods of obtaining the shear characteristics at a constant shear strain rate are compared: by programming a universal testing machine to achieve a nonlinear crosshead movement and by post-processing data obtained with a constant crosshead rate.

Proceedings of the 22nd International ESAFORM Conference on Material Forming
AIP Conf. Proc. 2113, 020001-1–020001-6; https://doi.org/10.1063/1.5112506
Published by AIP Publishing. 978-0-7354-1847-9/$30.00

EXPERIMENTAL TEST SETUP

The shear characterization is accomplished using a picture-frame rig mounted in a universal testing machine as shown in Fig. 1. The lower joint is fixed in position, and when the upper joint is displaced, the clamped material theoretically experiences a state of uniform shear.

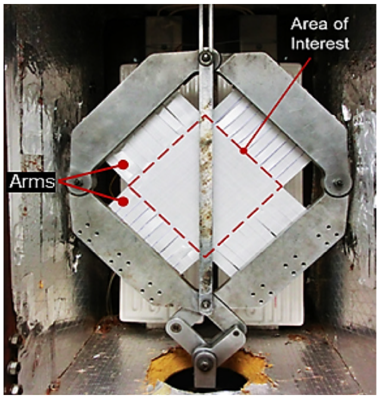


FIGURE 1. Picture frame setup. The frame is placed in an environmental chamber for testing at elevated temperatures. The area of interest or gage area is 136 × 136 mm.

Material Systems

The two material systems considered in this study are both high-performance composite materials. The first is a 4-harness satin-weave carbon-fiber (CF) prepreg with a Bismaleimide (BMI) matrix. The thickness is 0.3 mm, and the areal density is 314 g/m^2. The second material system is a thermoplastic pre-consolidated sheet comprised of ultrahigh molecular weight polyethylene (UHMWPE) fibers suspended in a polyurethane (PUR) matrix. It consists of four lamina with the configuration $(0/90)_2$ and has the commercial name Dyneema® HB80. The total ply thickness is 0.148 mm and the areal density is 145 g/m^2.

The two material systems are conceptually different in their composition which also influences the forming processes. Carbon-fiber prepregs can be formed at room temperature, whereas the thermoplastic sheets must be formed at elevated temperatures. In this study, the testing temperature was 90°C. For details on how this testing condition was accomplished, refer to Dangora et al. [6]. Their applications also differ. Carbon-fiber prepregs are, for instance, used in the aerospace industry, which demands high strength-to-weight and stiffness-to-weight ratios. The UHMWPE fibers also have attractive strength properties but also exhibit excellent toughness making them ideal for personal armor such as combat helmets.

Investigated Parameters

As mentioned in the introduction, a key question is, how the "arms" of the cruciform sample influence the uniformness of the shear strain field in the gage area. To investigate this question, the cruciform shape was modified in two ways: by cutting slits in the arms and by dissolving the matrix material whereby the cross fibers could be removed.

Regarding the cutting of slits, it was carried out using a ruler and a utility knife. For the CF prepreg, the slits were cut to the width of three tows or approximately 6 mm. For the thermoplastic cross-ply, the target width was 6 mm.

Regarding the dissolving of the matrix material, it was achieved using a solvent which would not damage the fibers. The solvents used were ethanol and acetone respectively for the CF prepreg and thermoplastic cross-ply. Care was taken so as not to get any solvent on the gage area and by means of a comb, the cross fibers were removed. Slitted-arms and dissolved-matrix samples are presented in Fig. 2.

When the frame is displaced at a constant crosshead rate, the kinematics of the frame (see the next section) entail that the shear strain rate experienced by the sample will be increasing. For rate sensitive materials, such as those considered in this study, it is of interest to perform the test at a constant shear rate. Therefore, a nonlinear

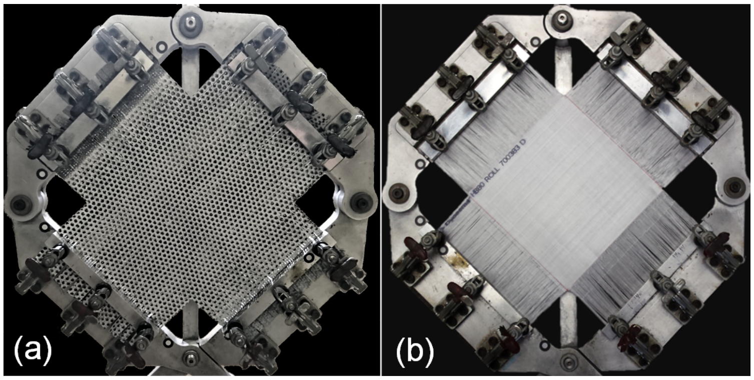


FIGURE 2. Test samples mounted in frame. (a) carbon-fiber prepreg with cut slits in arms and applied speckle pattern. (b) thermoplastic cross-ply with matrix and cross fibers removed.

cross-head velocity profile is generated based on the frame kinematics such that the shear rate will be constant. It is approximated using linear ramp segments in the Instron® test machine control software Bluehill® 3. Specifically, the implementation is done in the TestProfiler module. The constant target strain rate is 2.66°/s.

DATA ACQUISITION AND PROCESSING

This section presents how shear force and shear angles are obtained from the test. The global shear angle of the sample, γ, can be obtained from the length of the frame, L_F, and the measured crosshead displacement, δ [7]:

$$\gamma = \frac{\pi}{2} - 2\arccos\left(\frac{1}{\sqrt{2}} + \frac{\delta}{2L_F}\right) \tag{1}$$

The shear force on the sample is a function of the global shear angle, γ, and the measured crosshead force, F. It can be normalized using the length of the frame, L_F and the length of the fabric, L_f assuming no contributions from the arms [8]:

$$F_{sh,norm} = \frac{L_F}{L_f^2} F_{sh} \qquad , F_{sh} = \frac{F}{2\cos\left(\frac{\pi}{4} - \frac{\gamma}{2}\right)} \tag{2}$$

Digital Image Correlation

Using the 256 grayscale values in an 8-bit image, the sample deformation can be measured optically by means of Digital Image Correlation (DIC). The optical measurement provides a shear strain field in the sample rather than just the global shear angle from Equation (1). DIC works by correlating a sequence of deformed images to a reference image whereby a displacement field is obtained. By differentiating the displacement field, the strain field is obtained. The samples for both of the material systems were first coated with a matte white paint to enhance contrast and to reduce glare. Then, a black speckle pattern was applied to facilitate the correlation. The specifications of the setup are listed in Table 1.

TABLE 1. Key parameters in the DIC setup. Both setups apply 3D DIC using the GOM™ ARAMIS system.

	Carbon-Fiber Prepreg	**Thermoplastic Cross-ply**
Sensor	1624 × 1236 (2 MP)	4096 × 3072 (12 MP)
Recording frequency	10 Hz	8 Hz
Facet, step	10 × 10, 8	20 × 20, 19
Strain window	3 points	3 points
Shear strain resolution	0.05°	0.06°

RESULTS

This section presents the results of the study: the investigation of sample arm geometry and the constant shear rate data comparison.

The Effect of Sample Arm Geometry

The samples were prepared, tested and the optical measurements were evaluated. Figure 3 presents a comparison of the measured shear strain at a frame angle of 25.5° for the full-arm and slitted-arm samples. Table 2 presents some relevant data, including statistics. From Figure 3 and Table 2 it is seen that the strain fields in general are not uniform but that the mean values only are a few degrees behind the kinematic global angle from (1). A general observation is the effect of uneven sample tension which is evident as bands from one toggle clamp to another. Notice also how the arms are wrinkling slightly in the full-arm samples but not in the slitted-arm samples.

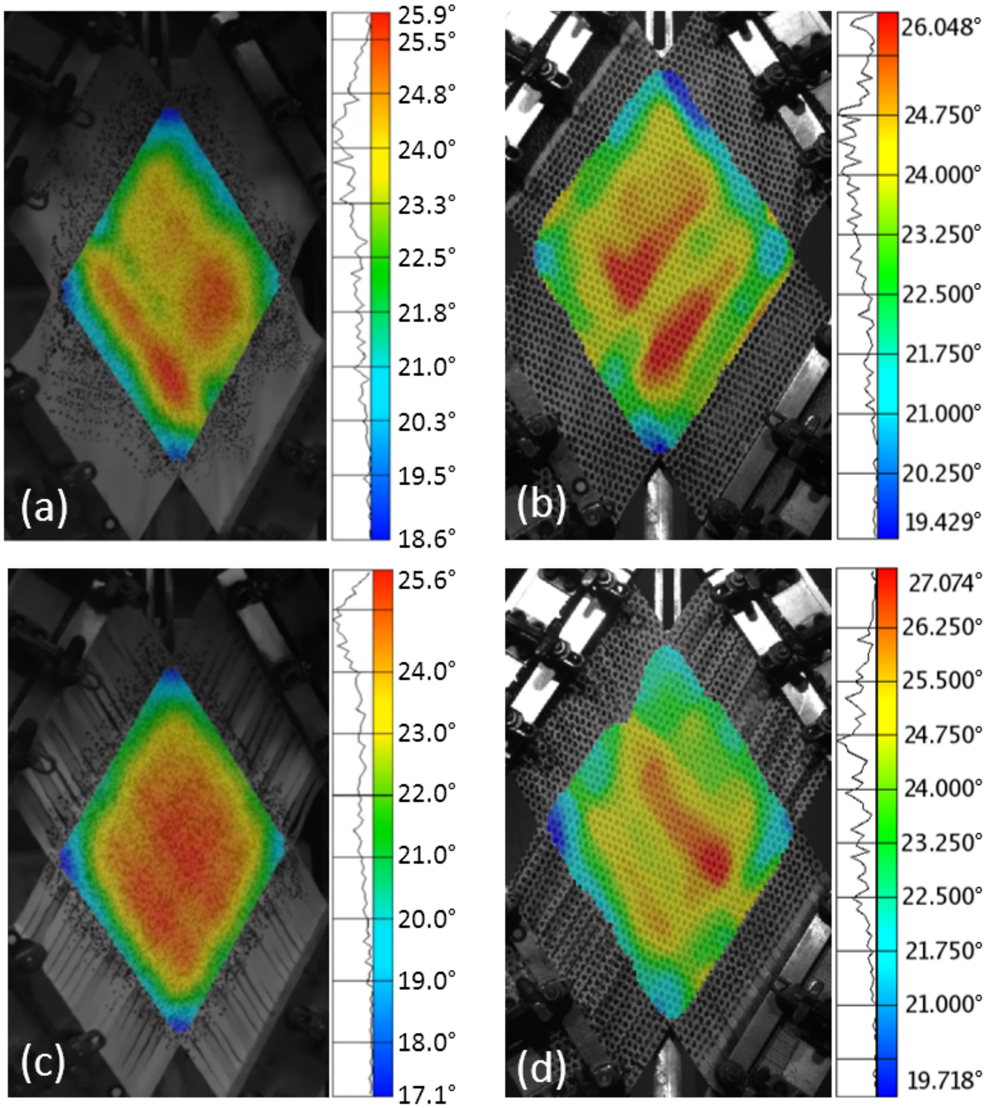


FIGURE 3. DIC shear strain fields at a frame angle of 25.5°. (a) Thermoplastic cross-ply, full arm. (b) CF prepreg, full arm. (c) Thermoplastic cross-ply, slits. (d) CF prepreg, slits. The contours span ±3σ.

Considering the effect of sample geometry for the thermoplastic cross-ply - (a) and (c) - there is a clear visual trend towards a more uniform shear angle distribution with the slitted arms. This observation is also supported by the histogram next to the color bar. The measured shear force is also 26% lower. For the carbon-fiber prepreg - (b) and (d) - the trend is not so obvious. The histogram suggests a slight improvement, but the main difference is observed on the shear load, which is decreased by 29%. It should be noted that the two material systems have a very different shear force vs. shear angle characteristic. This difference is expected because the mechanisms of shearing on the meso-scopic level are different. For woven materials, the interaction between the two fiber directions is much higher which is believed to cause the more pronounced effect with the uneven sample tension and less uniformity. For the cross-ply, however, the material architecture has a larger "smear-out" effect.

TABLE 2. Results from the DIC analysis.

	±3σ band	**Mean ±1σ**	**Norm. Shear Force (γ = 25.5°)***
Thermoplastic cross-ply, full	18.6 – 25.9°	22.3 ± 1.2°	190 N/m
Thermoplastic cross-ply, slits	17.1 – 25.6°	21.4 ± 1.4°	140 N/m
CF Prepreg, full	19.4 – 26.0°	22.7 ± 1.1°	189 N/m
CF Prepreg, slits	19.7 – 27.1°	23.4 ± 1.2°	135 N/m

* This is reported as the average value of the tested samples.

The samples with dissolved matrix material (not shown here) replicate the trend of a mean shear angle close to the frame angle but with an even lower shear force vs. shear angle characteristic. For the CF prepreg, though, an inferior shear angle uniformity was observed. For both material systems, it was concluded that the sample condition with dissolved matrix in the arms provided the more realistic measure of the shear behavior.

Constant Shear Rate Data

In the following, the results from the study of constant shear rate data are presented. First, using the average gage area values from the CF prepreg DIC measurements, it is checked that the implemented ramp segments in the test machine control software does indeed produce a constant shear rate. This result can be verified from Fig. 4 (b) where fabric shear angle vs. time maps to a straight line. Next, it is investigated if constant shear rate data can be post-processed from constant cross-head data. In a previous study, the CF prepreg material was characterized using the bias-extension test at three constant cross-head rates [9]. Using these data as the basis for a C^1-continuous surface interpolation of the cross-head force vs. shear angle and shear angle rate (Fig. 5 (a)), a "slice" of the surface can be taken at a constant shear angle rate of 2.66°/s. The result is presented in Fig. 5 (b). The figure also includes the average results of three bias-extension tests obtained using a programmed constant shear rate and the result of the picture-frame test from the present section with the dissolved-matrix samples. The graph indicates that the surface-interpolation approach can give an estimation of the constant shear rate behavior but that some error is introduced. However, this error is approximately the same order of magnitude as that between the bias-extension test and the picture-frame test.

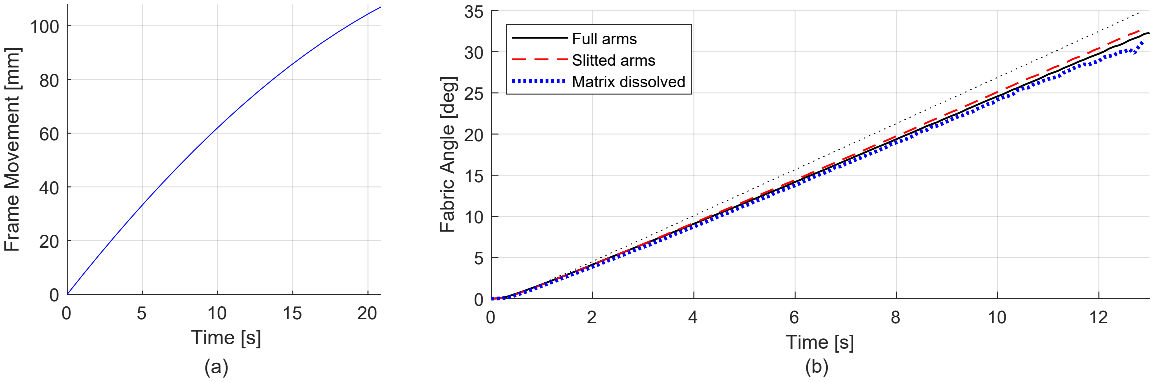
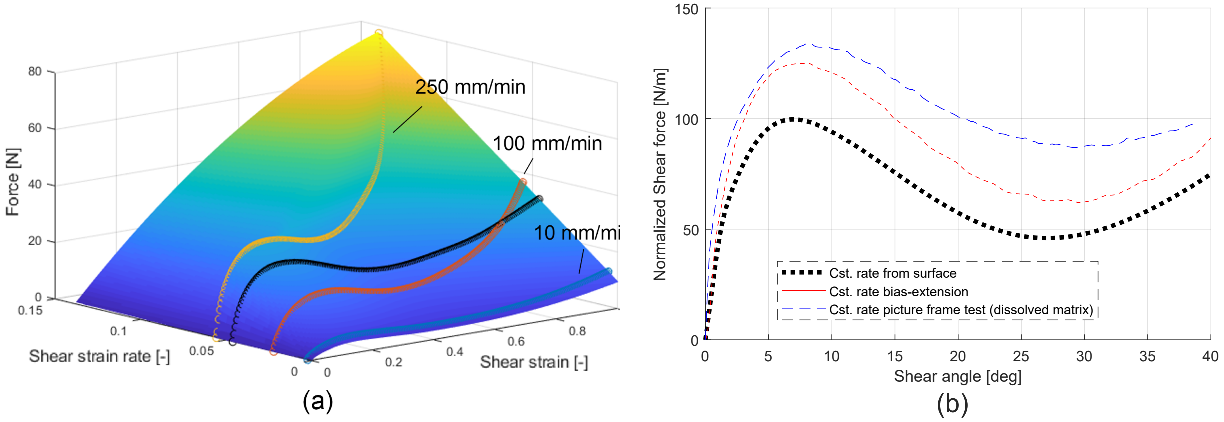


FIGURE 4. Testing at a constant shear rate. (a): Frame movement vs. time. (b) Average fabric angle from DIC vs. test time. The black dotted line indicate the kinematic frame angle from Equation (1). The frame has an angle of 25.5°at approximately 9.5 s.



(a) (b)

FIGURE 5. Generation of constant shear rate data for CF prepreg. (a) Interpolated surface. (b) Comparison of normalized shear force vs. shear angle curves from interpolated surface, constant shear rate bias-extension tests and constant shear rate picture-frame tests. All data at 2.66°/s.

CONCLUSIONS

This paper has presented a study of the influence of the sample arm geometry in the picture-frame test and an investigation of the concept of testing at a constant shear rate. Regarding the influence of sample geometry, it was found that cutting of slits had a pronounced effect on the uniformity in the thermoplastic cross-ply samples whereas the effect was essentially negligible in the carbon-fiber prepreg samples. However, for both material systems, the force required to shear the samples was significantly lower and only the condition with dissolved matrix provided realistic results. Testing at a constant shear rate was achieved by programming the tensile test machine and post-processing constant cross-head data by means of an interpolating surface. The multi-linear ramp approximation implemented in the test machine control software was found to be adequate to make the shear rate of the fabric constant. The surface interpolation approach appears to give a good approximation of a constant shear rate test. The comparison between bias-extension tests and picture-frame tests showed some discrepancy which highlights that there is still progress to be made regarding material shear characterization.

ACKNOWLEDGMENTS

The authors would like to thank Terma Aerostructures A/S for providing part of the material for the research. The authors also acknowledge Alessandro Sabato, UMass Lowell, for his contributions to the DIC analysis.

REFERENCES

[1] M. Nguyen, I. Herszberg, and R. Paton, Composite Structures **47**, 767–779 (1999).
[2] X. Peng and J. Cao, Composites Part A: Applied Science and Manufacturing **36**, 859–874 (2005).
[3] R. P. Mohan, H. Alshahrani, and M. Hojjati, Journal of Composite Materials **50**, 4251–4268 (2016).
[4] P. Harrison, M. Clifford, and A. Long, Plastics, Rubber and Composites **31**, 1–12 (2002).
[5] B. Zhu, T. X. Yu, and X. M. Tao, Composites Science and Technology **67**, 252–261 (2007).
[6] L. M. Dangora, C. J. Hansen, C. J. Mitchell, J. A. Sherwood, and J. C. Parker, Composites Part A: Applied Science and Manufacturing **78**, 181–190 (2015).
[7] J. Cao, R. Akkerman, P. Boisse, J. Chen, H. S. Cheng, E. F. de Graaf, J. L. Gorczyca, P. Harrison, G. Hivet, J. Launay, W. Lee, L. Liu, S. V. Lomov, A. Long, E. de Luycker, F. Morestin, J. Padvoiskis, X. Peng, J. A. Sherwood, T. Stoilova, X. Tao, I. Verpoest, A. Willems, J. Wiggers, T. Yu, and B. Zhu, Composites Part A: Applied Science and Manufacturing **39**, 1037–1053 (2008).
[8] X. Peng, J. Cao, J. Chen, P. Xue, D. S. Lussier, and L. Liu, Composites Science and Technology **64**, 11–21 (2004).
[9] C. Krogh, J. A. Glud, and J. Jakobsen, Journal of Composite Materials (2019), in press.