3D digital image correlation measurements during shaping of a non-crimp 3D orthogonal woven E-glass reinforcement

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Introduction

During the manufacturing process of composite reinforcements, a crucial step is the forming of a flat textile into a three-dimensional shape. After shaping, the preform is injected with resin and consolidated. The shape of the preform is generally obtained by a punch and die forming process. The deformation mechanisms occurring during such processes, are an important knowledge in prediction of the permeability of the preform and thus, in the mechanical quality of the composite component [1].

Digital image correlation (DIC) is a contactless technique which offers qualitative and quantitative information on the heterogeneous deformation of an object surface. It provides a full-field displacement over a two- or three- dimensional surface, by comparing images of speckled specimen surfaces before and after deformation. In the last years, in the field of textile composites reinforcements, optical full-field strain measurements have been used for studying: (i) the shear and tensile behaviour of fabrics by bias extension, picture frame and biaxial tests (e.g. [2, 3]); (ii) the local deformation mechanisms occurring during mechanical testing, at the level of the reinforcement unit cell and of the individual yarns (e.g. [4]); and finally (iii) to measure the 3D-deformed shape and the distribution of local deformations of a textile reinforcement after forming processes (e.g. [5–7]). In [8], the importance of the digital image correlation technique for composite reinforcements characterization is pointed out, mainly due to the adequate determination of the strain field on the specimen surface. Moreover, the authors showed that measurement of the local deformations by means of image correlation on a composite component after forming provides a convenient tool for the determination of the local fibre orientations and shear angles.

In this work, an experimental investigation of a 3D textile composite reinforcement during forming processes is presented. In particular, being the shear deformation considered as the primary deformation mechanism in the shaping process of reinforcements [9], the evolution of shear angle distribution during such process is measured by means of 3D DIC analyses. For this purpose, two different image correlation software

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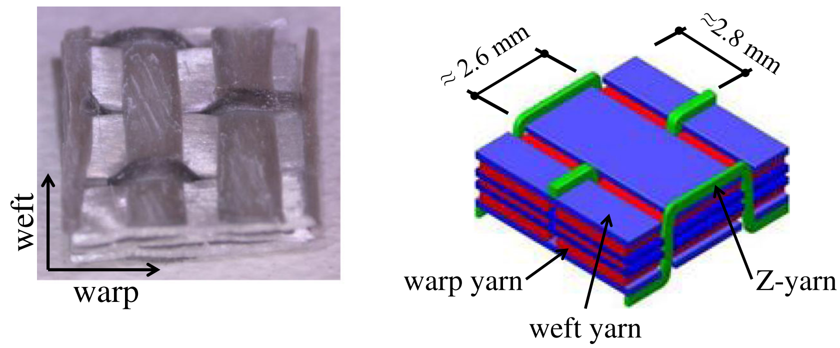


Fig. 1 Architecture of the tows inside the non-crimp 3D orthogonal weave preform [13]: photo (*left*) and sketch (*right*) of the unit cell

programs, namely VIC-3D [10] and MatchID3D [11], are used and compared.

A single layer E-glass non-crimp 3D orthogonal woven reinforcement (commercialized under trademark 3WEAVE® by 3Tex Inc.) is shaped on two moulds, i.e. tetrahedral and double-dome.

The DIC contactless method provides important information on the complex shape formability of this 3D composite reinforcements having growing interest in the composites industry for a broad range of applications [12].

Non-crimp 3D orthogonal woven reinforcement

The material investigated during forming processes is a single layer E-glass non-crimp 3D orthogonal woven reinforcement (commercialized under trademark 3WEAVE® by 3Tex Inc.). The fibres architecture of the preform has three warp and four weft layers, interlaced by through thickness (Z-directional) yarns (Fig. 1 [13]). The fabric construction results in a ~49 %/~49 %/~2 % ratio of the fibres amounts (by volume) in the warp, weft and Z fibre directions, respectively. The fibre material is PPG Hybon 2022 E-glass. Some features of the non-crimp 3D orthogonal weave reinforcement are listed in Table 1.

The reader is referred to [14] for a detailed description of the preform architecture, studied with optical microscopy and micro-CT. Moreover, the mechanical properties during forming of the 3D glass reinforcement are illustrated in [3].

Table 1 Properties of the non-crimp 3D orthogonal weave preform. Data provided by 3Tex Inc

	Fabric plies	1
	Areal density (g/m^2)	3255
Warp yarns	Insertion density (ends/cm)	2.76
	Top and bottom layer yarns (tex)	2275
	Middle layer yarns (tex)	1100
Weft yarns	Insertion density (ends/cm)	2.64
	Yarns (tex)	1470
Z yarns	Insertion density (ends/cm)	2.76
	Yarns (tex)	1800

Experimental details

Experimental set-up

The forming process of the above mentioned 3D composite reinforcement is investigated with the set-up illustrated in Fig. 2. It consists of metallic components and optical instruments. Two steel punches with complex shapes (i.e. tetrahedral and double-dome), and two steel open dies are used. The tetrahedral punch is similar to the one adopted in [7], while the double-dome mould is that used in [15] for the thermoforming process of glass-PP woven fabrics. Geometry and dimensions of the tools are illustrated in Fig. 3. The optical part of the set-up consists of a stereo vision system (Fig. 2), which acquires digital images of the forming process at a frequency of 1 Hz. These images are analysed for 3D image correlation by VIC-3D [10] and MatchID3D [11].

Rectangular specimens of the 3D reinforcement (500× 600 mm) are placed unclamped on the open die. The punch moves downwards for 65 mm at a constant rate of 10 mm/min.

The moulds are mounted on an Instron 5567 tensile machine, measuring the load with a cell of 30 kN.

3D digital image correlation

This section focuses on the optical part of the set-up and the software settings used for the 3D digital image correlation analyses. The optical instruments are two digital 2/3″ CCD cameras (image size 1,392×1,040, 1.45 MP) with Schneider Xenoplan 2.8/50 mm lenses, mounted vibration-free on the bottom of the open die at approximately 470 mm (see Fig. 2a). This distance, combined with an aperture setting of f/8, ensures that the reinforcement is completely visible in the field of view of the cameras (see Fig. 4), and that the necessary depth of field (approximately 65 mm) is achieved. The pixel resolution for the tetrahedral and double-dome set-up is about 5 px/mm. The stereo system is calibrated with a 12×9 dots

Fig. 2 (**a**) Tetrahedral and (**b**) double-dome forming test set-up

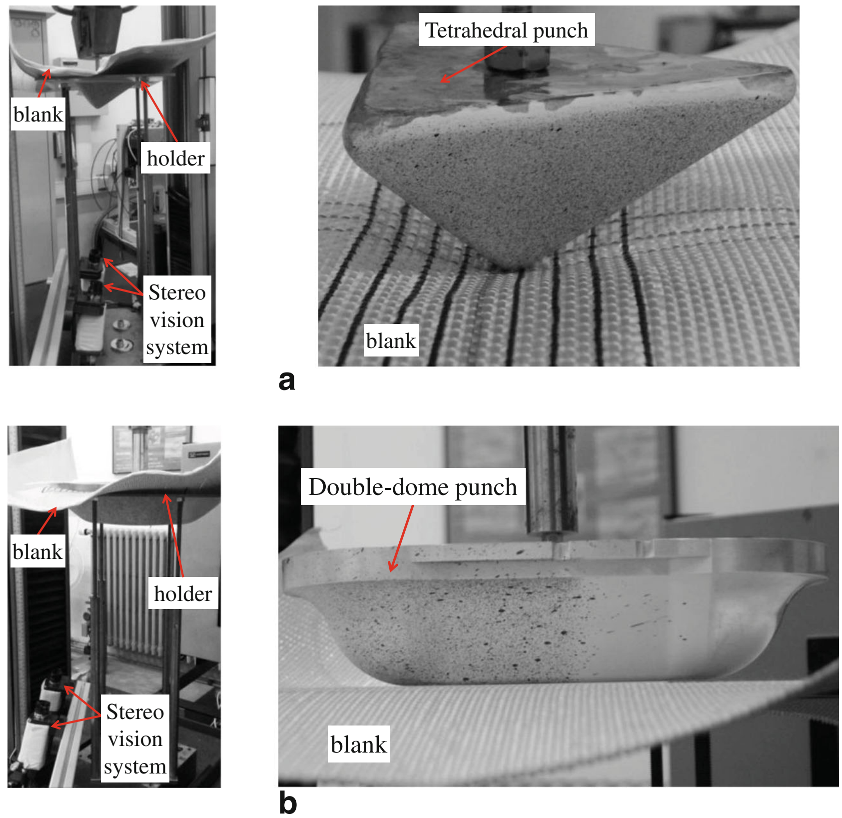
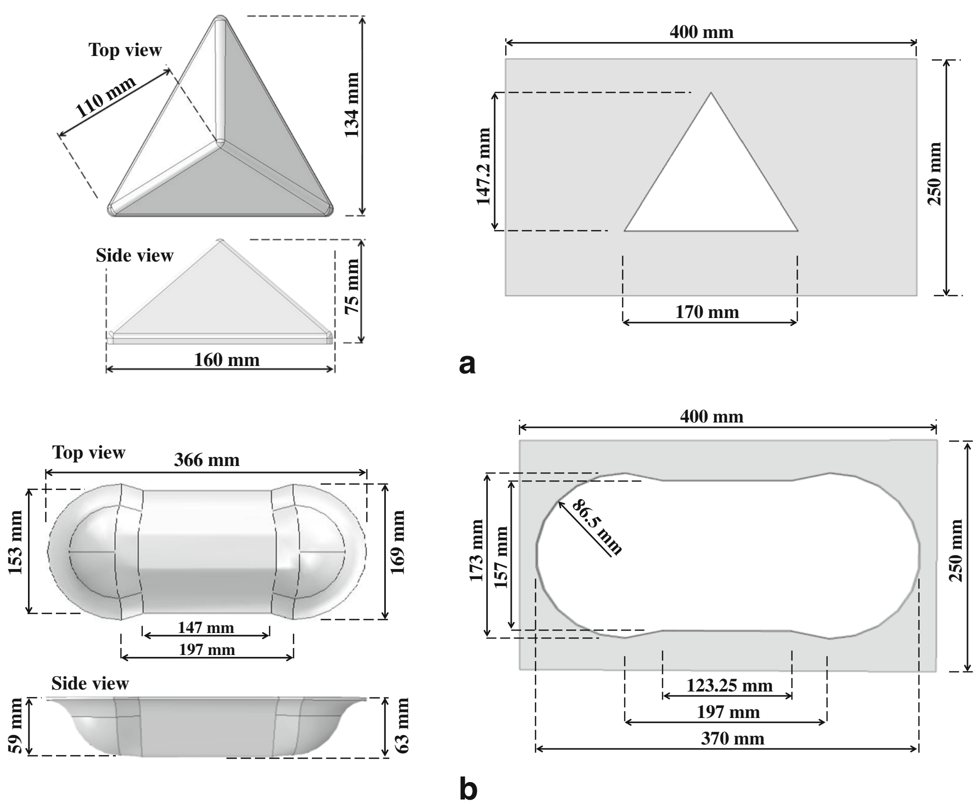


Fig. 3 Dimensions of the forming tools: (**a**) tetrahedron (*left*) and its open die (*right*); (**b**) double-dome (*left*) and its open die (*right*)



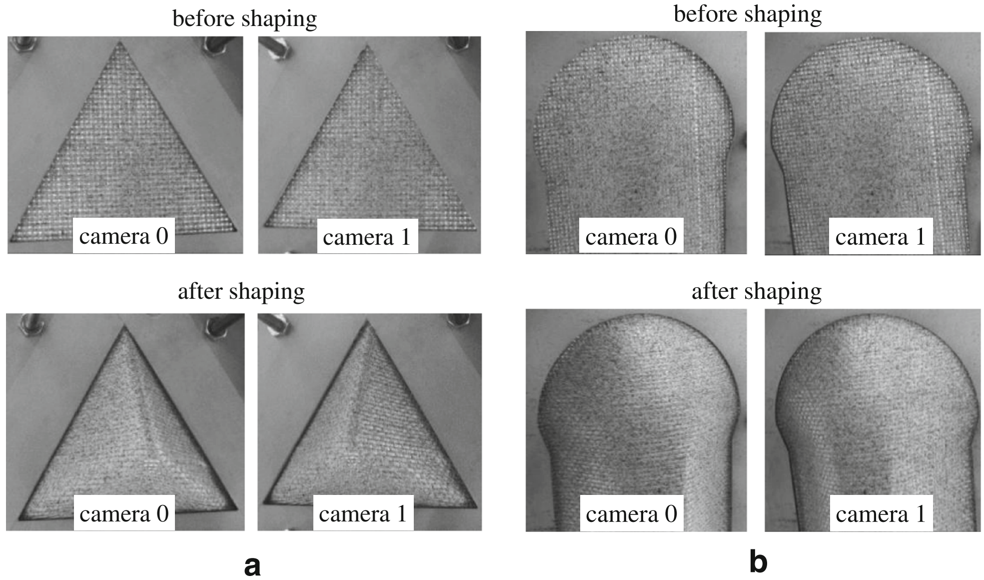


Fig. 4 Field of view of cameras before and after shaping: (**a**) tetrahedral and (**b**) double-dome forming

calibration pattern with an inner dots distance of 6.02 mm and 9.01 mm for the tetrahedral and double-dome punch, respectively. Calibration is executed in the calibration module of VIC3D. The obtained parameters are used for the correlations with VIC3D and MatchID3D to exclude possible calibration errors. Intrinsic and extrinsic camera parameters are listed in Table 2.

Concerning the reinforcement preparation, the specimen surface is lightly sprayed with white and black acrylic paint (see Fig. 4) in order to get a random, non-repetitive, isotropic and high contrast speckle pattern, necessary for accurate displacement measurements [16]. During the test, images are acquired at a rate of 1 Hz, corresponding to a vertical increment of the punch of about 0.167 mm.

The correlation and calculation of the displacements of the speckle patterns is performed with the two correlation software packages: the commercial software VIC-3D [10] and the academic software MatchID3D [11], developed at Catholic University College of Ghent. The correlation settings used for both software packages are listed in Table 3. The spatial resolution, often interpreted as the complete independent area needed to calculate a specific quantity, for strain calculations in both platforms is defined as $(Sw-1)\times St+Ss$; where Sw, St and Ss are the strain window, the step and the subset, respectively.

The main benefit of digital image correlation is the ability to perform a full-field displacement measurement by means of a contactless technique. One drawback could be the

Table 2 Camera parameters after a calibration with VIC-3D; two values of the same parameter refers to camera 0 and camera 1, respectively

	Parameter	Double-dome	Tetrahedron
Intrinsic	Focal length in X [px] - fx	2523.71/2539.23	2526.51/2543.24
	Focal length in Y [px] - fy	2522.81/2538.83	2527.66/2543.93
	Focal point skew [px] - fs	−0.244627/0.237266	0.678489/−0.30637
	Principle point X [px] - cx	717.582/679.705	726.67/681.416
	Principle point Y [px] - cy	526.571/513.564	535.388/530.324
	Spherical Distortion Kappa 1	−0.145075/ −0.140043	−0.149178/ −0.140605
Extrinsic	X translation [mm] - Tx	−189.646	213.945
	Y translation [mm] - Ty	2.13313	−2.19175
	Z translation [mm] - Tz	35.217	43.7965
	Rotation angle about optical axis Alpha [deg]	0.237273	−1.49954
	Stereo rotation angle Beta [deg]	23.111	−26.2971
	Tilt angle Gamma [deg]	1.16553	1.00684
	Baseline [mm]	192.888	218.393
	Distance to camera [mm]	471	467

Table 3 Comparison of the correlation settings for VIC-3D and MatchID3D

Correlation Software	VIC-3D	MatchID3D
Correlation algorithm	Normalized sum square differences (NSSD)	Zero-normalized cross-correlation (ZNCC)
Interpolation	Optimized 8-tap	Bicubic polynomial interpolation
(Stereo) Transformation		Affine
Correlation progress	Incremental	Spatial + Update ref.
Subset weights/Noise handling	Gaussian	Gaussian
Strain tensor	Green-Lagrange	Green-Lagrange
Filter size [px]/Strain window	15	15
Subset size [px^2]	40×40	40×40
Step size [px]	3 for tetrahedron	3 for tetrahedron
	5 for double-dome	5 for double-dome
Spatial strain resolution [px]	82 for tetrahedron	82 for tetrahedron
	110 for double-dome	110 for double-dome

degradation of the pattern in high deformed parts resulting in zones without data due to the loss of correlation.

Results and comparisons

The 'grid method', adopted in [8] during forming of 2D composite reinforcements, is used to measure local deformations of the 3D fabric during shaping. The grid consists of facets, made by spacing of points (i.e. step size in pixels), in the Area of Interest (AoI) analysed during correlation. For each recorded incremental position of the mould, the 3D displacement in the field of view of the cameras is obtained with DIC. The recorded data allows post-processing for evaluation of the local shear angle as the variation, with respect to the un-deformed shape, of the angle between initial orthogonal segments. Assuming a box as a set of facets, the local shear angle (γ) is quantified as: $\gamma = \alpha_f - \alpha_i$, where, a_i and a_f are the angles between the two consecutive sides of a box in the un-deformed and deformed configuration, respectively. Each box is square in the initial configuration and is made of 10×10 and 6×6 facets for the tetrahedron and double-dome respectively. The adopted box dimensions are such that its size is very close to the unit cell of the considered 3D textile (≈6×6 mm^2), for the evaluation of the shear angle at the meso-scale. The steps carried out to measure the shear angle distribution on the reinforcement surface are summarized in Fig. 5.

For both shapes, the specimens had the initial yarn directions parallel to the die's sides. Four specimens for each forming shape are used. The results obtained with VIC-3D and MatchID3D software, are compared in terms of displacements and shear angles distribution, for a tetrahedral punch displacement

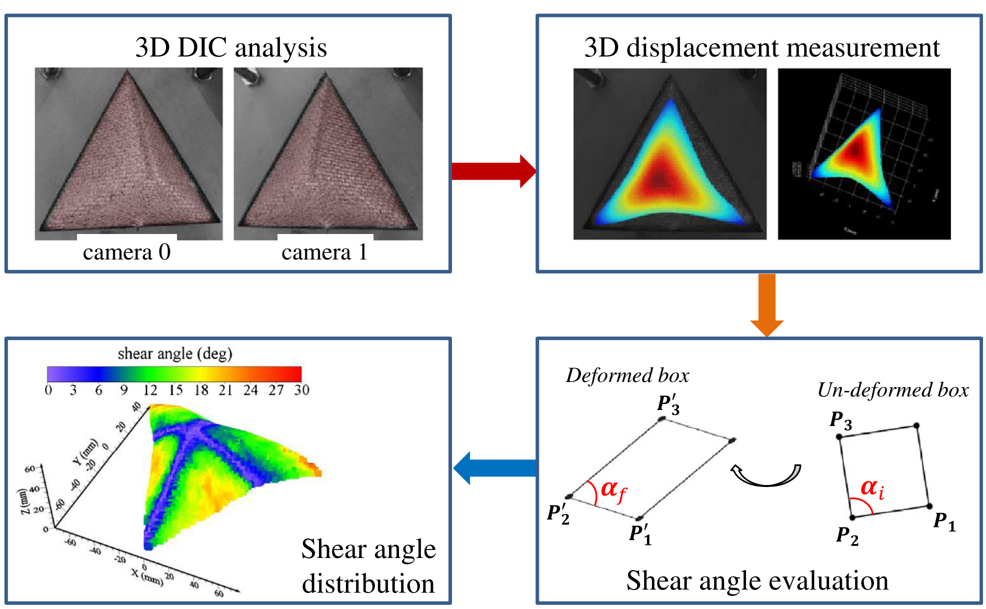


Fig. 5 Steps for local shear angle calculation by 3D digital image correlation analysis

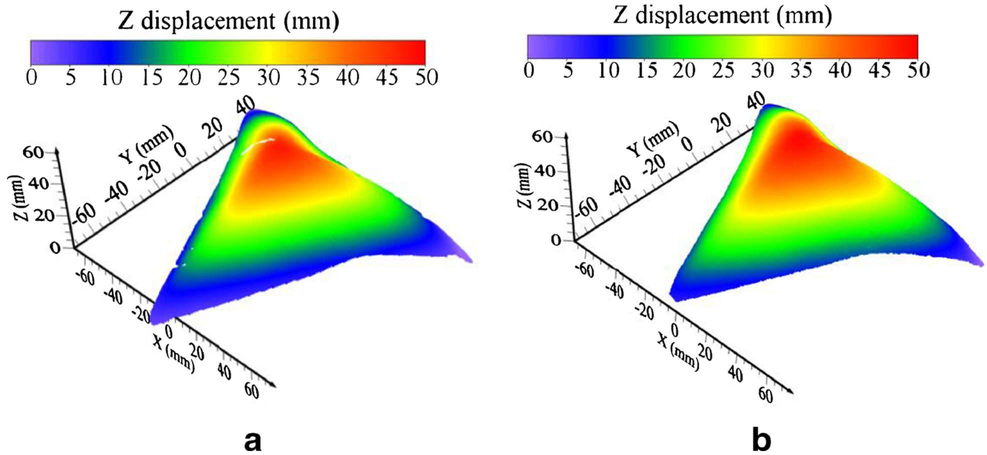


Fig. 6 Tetrahedron formability test. Displacement field on the reinforcement surface for 50 mm of punch displacement by: (**a**) VIC-3D and (b) MatchID3D

of 50 mm, and at the end of the double-dome forming process (punch displacement of 65 mm). The data for the tetrahedron are presented for a lower punch displacement due to the lack of correlation in some parts of the surface at the end of the shaping.

Since displacements are the input for shear angle calculation, the first assessment of the accuracy of the two measurement devices involves the 3D displacement field of the deformed configuration. Figures 6 and 7 show the displacement field on the observed AoI surface of one specimen for each considered shape. The contour plots demonstrate agreement of the displacement fields. The discrepancy between the measurements is represented in Fig. 8, where the difference of the shapes is highlighted. The maximum difference of the displacement is below 5 % of the maximum imposed punch displacement. This is due to the different correlation algorithms and could be considered negligible for the deformability assessment of the considered 3D reinforcement.

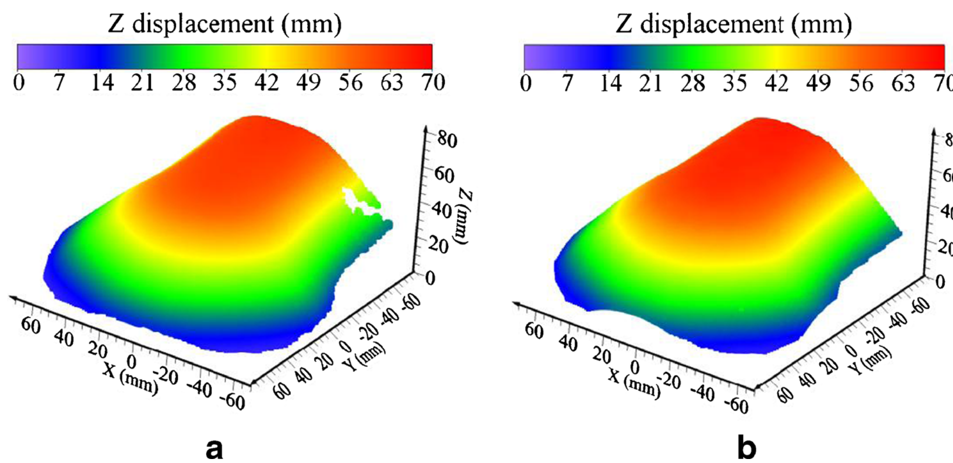


Fig. 7 Double-dome formability test. Displacement field on the reinforcement surface at the end of shaping process by: (**a**) VIC-3D and (**b**) MatchID3D

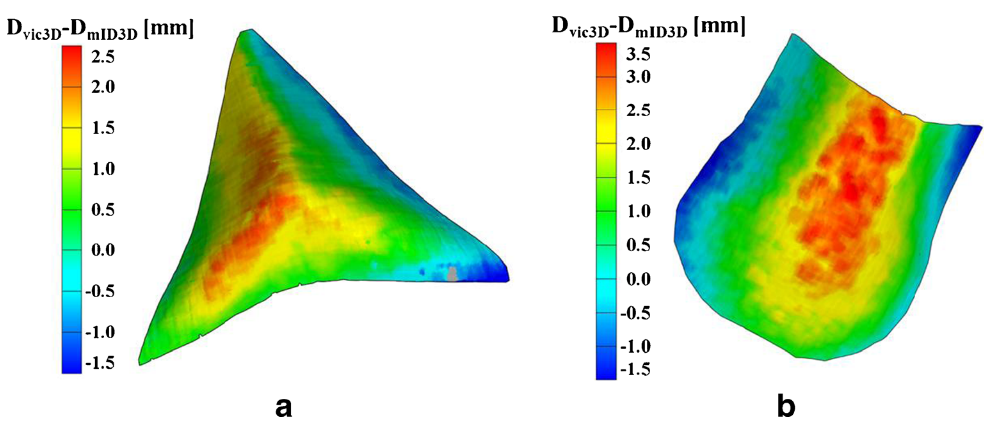


Fig. 8 Difference of the recorded shapes measured by the two DIC software. (**a**) tetrahedron; (**b**) double-dome

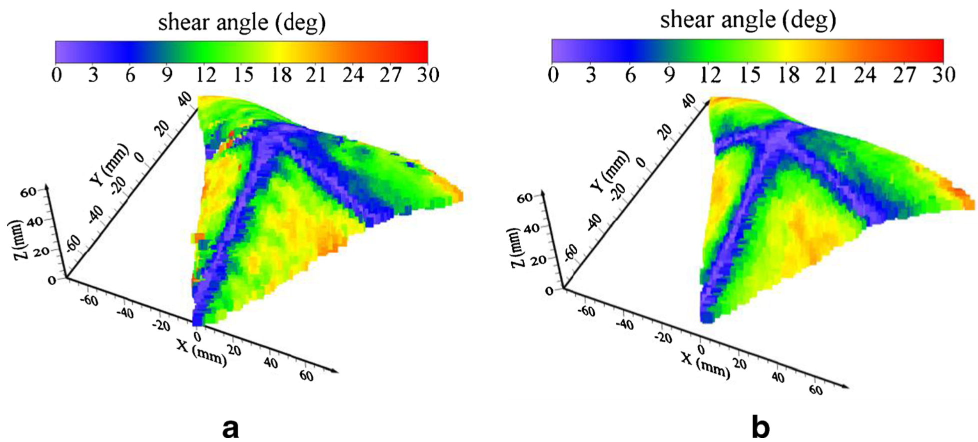


Fig. 9 Tetrahedron formability test. Shear angle distribution on the reinforcement surface for 50 mm of punch displacement by: (**a**) VIC-3D and (**b**) MatchID3D

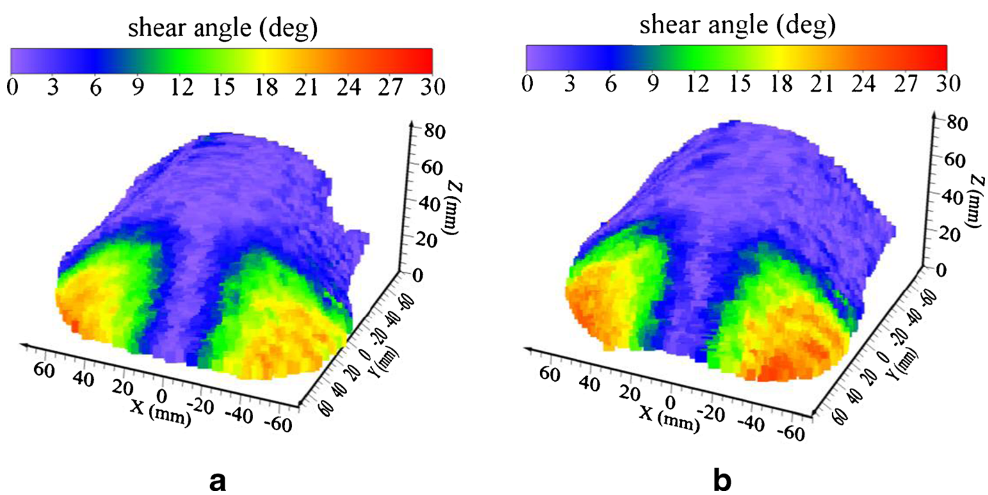


Fig. 10 Double-dome formability test. Shear angle distribution on the reinforcement surface at the end of forming process by: (**a**) VIC-3D and (b) MatchID3D

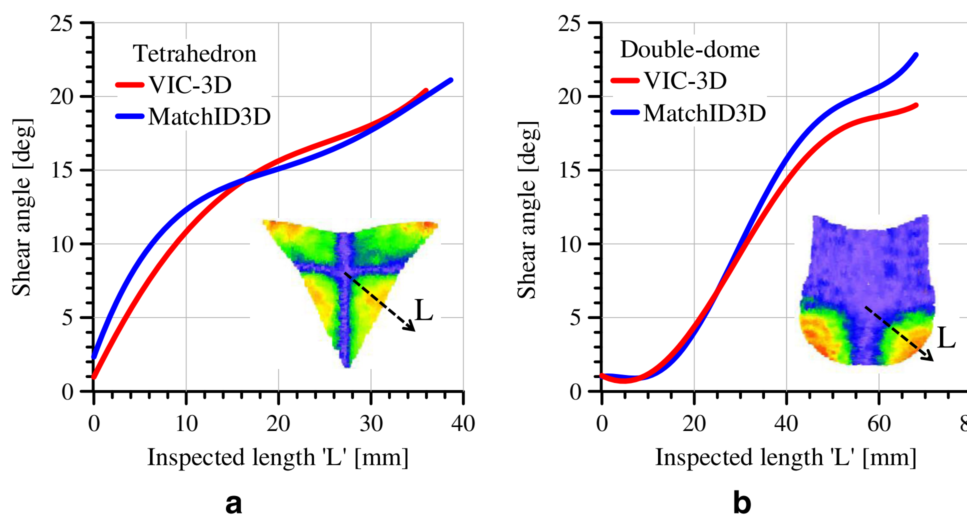


Fig. 11 Comparison of the shear angle along one segment on the surface at the end of forming process. Polynomial fitting for: (**a**) tetrahedron; (**b**) double-dome

Post-processing of the three-dimensional displacement field allows evaluation of the shear angle distribution inside the AoI of the preform surface. Figure 9 shows shear angles produced during the tetrahedral forming evaluated with input of both DIC packages. The shaping of the 3D reinforcement generates shear angles lower than about 23 deg, for a punch displacement of 50 mm. The maps in Fig. 9 indicate a larger concentration of shear angles located on the face sides of the tetrahedron. The comparison of the predicted shear angle with the two DIC displacement fields is presented in Fig. 11a. Along a segment in the maximum shear angle concentration zone, the difference is below 2 deg. This can be considered acceptable being the main purpose of the measurements the evaluation of the shear angle distribution on the complete forming shape and considering the different correlation algorithms adopted.

Forming of the double-dome gives the shear angle diagrams in Fig. 10. VIC-3D and MatchID3D provide shear angle not exceeding 25 deg. The concentration of the higher shear angles is in the higher curvature zones, bottom right and left in Fig. 10. In Fig. 11b, the comparison of the shear angle along a segment in the maximum concentration zone shows the larger difference below 3 deg. As above mentioned, considering the main purpose of this work, the obtained shear angle distributions can be considered accurate.

Overall, the comparisons, detailed in Figs 6, 7, 9, and 10, show a good agreement between the measurements obtained by VIC-3D and MatchID3D. Furthermore, these results demonstrate that 3D digital image correlation technique can be very useful for the continuous measurement and monitoring of complex shape forming processes with 3D composite reinforcements, and in particular with the considered E-glass non-crimp 3D orthogonal woven fabric.

Conclusions

The presented experimental investigation is dedicated to the forming process of a single layer E-glass non-crimp 3D orthogonal woven reinforcement (commercialized under trademark 3WEAVE® by 3Tex Inc.). The adopted methodology involves the application of 3D digital image correlation technique for continuous measurement of the local deformation during forming.

The experimental results show a good agreement between the measurements obtained by two software packages, namely VIC-3D and MatchID3D. The results gathered by 3D digital image correlation analyses, reveal the adequacy of this technique to measure displacement based quantities (e.g. shear angle), during complex shape forming processes of 3D composite reinforcements.

The collected data constitute an extensive dataset for the assessment of numerical methods predicting the complex shape forming behaviour of such 3D reinforcement for composite materials. The input data for such calculation are the measurements of the shear and tension deformation response of the 3D reinforcement detailed in [3].

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References

1. Boisse P (2011) Composite reinforcements for optimum performance, Woodhead Publishing Limited
2. Willems A, Lomov SV, Verpoest I, Vandepitte D (2009) Drapeability characterization of textile composite reinforcements using digital image correlation. Opt Lasers Eng 47:343–351
3. Carvelli V, Pazmino J, Lomov SV, Verpoest I (2012) Deformability of a non-crimp 3D orthogonal weave E-glass composite reinforcement. Compos Sci Technol 73:9–18
4. Launay J, Hivet G, Duong AV, Boisse P (2008) Experimental analysis of the influence of tensions on in plane shear behaviour of woven composite reinforcements. Compos Sci Technol 68:506–515
5. Vanclooster K, Lomov SV, Verpoest I (2009) Experimental validation of forming simulations of fabric reinforced polymers using an unsymmetrical mould configuration. Composites: Part A 40:530–539
6. Khan MA, Mabrouki T, Vidal-Sallè E, Boisse P (2010) Numerical and experimental analyses of woven composite reinforcement forming using a hypoelastic behaviour. Application to the double dome benchmark. J Mater Process Technol 210:378–388
7. Allaoui S, Boisse P, Chatel S, Hamila N, Hivet G, Soulat D, Vidal-Salle E (2011) Experimental and numerical analyses of textile reinforcement forming of a tetrahedral shape. Composites: Part A 42:612–622
8. Lomov SV, Boisse P, Deluycker E, Morestin F, Vanclooster K, Vandepitte D, Verpoest I (2008) Full-field strain measurements in textile deformability studies. Composites: Part A 38:1232–1244
9. Polturi P, Parlak I, Ramgulam R, Sagar TV (2006) Analysis of tow deformations in textile preforms subjected to forming forces. Compos Sci Technol 66:297–305
10. Correlated Solutions, Inc. (2012) VIC-3D, Irmo, SC, USA: http://www.correlatedsolutions.com
11. MatchID - Image Correlation & Material Identification Mechanics of Materials, Products & Processes, http://www.matchid.org/, 2012
12. Bogdanovich AE, Mohamed MH (2009) Three- dimensional reinforcement for composites. SAMPE J 45:8–28
13. Carvelli V, Gramellini G, Lomov SV, Bogdanovich AE, Mungalov DD, Verpoest I (2010) Fatigue behaviour of non-crimp 3D orthogonal weave and multi-layer plain weave E-glass reinforced composites. Compos Sci Technol 70:2068–2076
14. Desplentere F, Lomov SV, Woerdeman DL, Verpoest I, Wevers M, Bogdanovich A (2005) Micro-CT characterization of variability in 3D textile architecture. Compos Sci Technol 65:1920–1930
15. Willems A (2008) Forming simulation of textile reinforced shell structures - PhD. Thesis, Katholieke Universiteit Leuven
16. Sutton MA, Orteu JJ, Shreir HW (2009) Image correlation for shape, motion and deformation measurements: basic concepts, theory and applications, Springer