DAMAGE CHARACTERIZATION IN MULTIDIRECTIONAL GLASS FIBRE REINFORCED POLYPROPYLENE LAMINATES UNDER QUASI-STATIC LOADING: EXPERIMENT & SIMULATION

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Abstract: *The quantification of matrix cracking during in-plane tensile experiments is challenging, particularly when opaque composites with complex lay-ups are concerned. In this study, experimental damage characterizations are performed for multidirectional laminates made of Glass/Polypropylene tapes under uniaxial tension loadings. Stereo Digital Image Correlation is implemented to measure strain fields and crack evolutions on the front and the edge surfaces of flat coupons. A damage detection methodology is developed to detect matrix cracking in the off-axis plies based on displacement discontinuities. Four multidirectional laminates with $[0_2/90]_{2s}$, $[90_2/0_2]_s$, $[0/45/0/-45]_s$, and $[0/45/90/-45]_s$ lay-ups are characterized to investigate the effects on crack initiation and growth. To validate the experimental measurements, post-mortem in-situ microscopy and a recent physics-based modelling technique are considered that can predict ply cracking, delamination and fibre breakage evolution and estimate the effects of damage modes on laminate properties. Good agreements are observed between the experimental and modelling results.*

Keywords: Thermoplastic composite; multidirectional laminates; damage characterization; in-situ instrumentation; physics-based modelling

1. Introduction

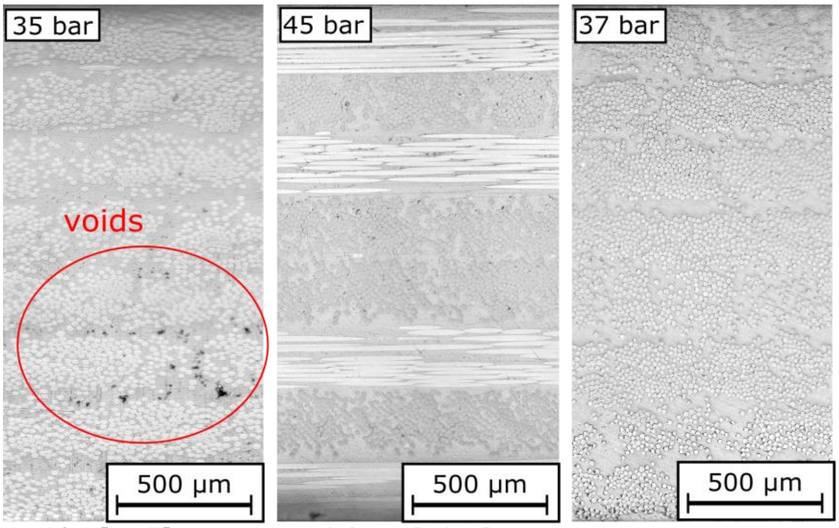
The observation of damage modes in multidirectional composite laminates without stopping the test is a cumbersome task. Visual inspection methods, such as photographs or advanced illumination techniques can provide useful insights into crack characteristics for transparent composites (e.g. glass/epoxy). Unfortunately, a broad range of composites is rather opaque, as is the case for Glass/Polypropylene (glass/PP). Recently, Digital Image Correlation, an optical-based instrumentation technique, has been used to assess matrix cracks in multidirectional carbon/epoxy laminates under bending loads [1] and in glass/epoxy laminates under in-plane loadings [2] with good agreement to post-mortem microscopy.

In the current research, we aim to perform a comprehensive damage characterization under uniaxial quasi-static tensile loading for multidirectional glass/PP laminates as this composite is an interesting alternative in large batch applications. To do so, a consistent manufacturing process based on hot-press moulding is implemented to produce glass/PP plates with reliable material properties, e.g. same fibre volume fraction for different stacking sequences. Four lay-ups, $[0_2/90_2]_s$, $[90_2/0_2]_s$, $[0/45/0/-45]_s$ and $[0/45/90/-45]_s$ are investigated to study the effects of laminate stacking sequence and ply thickness on the mechanical performance, crack initiation and progression. The effective mechanical performance and damage quantification are measured by two Stereo Digital Image Correlation (3D-DIC) systems. One 3D-DIC system is devoted to measuring full-field strains with validation by an extensometer in the axial direction. The other 3D-DIC system is designed for in-situ damage measurements on the specimen's edge surface with validation by post-mortem microscopy. For each laminate, the axial and transverse strains together with crack density in different off-axis plies are determined. The experimental results are further validated using a recently developed physics-based modelling technique [3, 4] based on the variational approach [5] and energy-based [6] failure criteria. To provide the required elastic properties for modelling inputs, basic laminates, $[0]_8$, $[90]_8$ and $[\pm 45]_{2s}$ are manufactured and tested.

2. Material and experimental methods

2.1 The manufacturing process and sample preparation

Unidirectional glass fibre reinforced polypropylene (glass/PP) tapes, namely UDMAX™ GPP 45-70 (SABIC FRT Tapes) are used for the production of uni- and multidirectional laminates by hot-pressing. The initial tape fibre volume fraction is 45 % with a nominal ply thickness of 0.25 mm. A maleic-anhydride modified isotactic polypropylene is used in the glass/PP tapes to improve the fibre-polymer adhesion and mechanical performance. All laminates are produced in a closed mould with (i) a heating phase to 210 °C with 4.5 K/min under 0.5 bar pressure, (ii) a holding phase of 10 minutes to ensure homogeneous temperature distribution, and (iii) a cooling phase to 50 °C with -8.5 K/min while applying 37 bar pressure for unidirectional and 45 bar for multidirectional laminates, respectively during consolidation. The pressure profiles are adjusted to achieve comparable plate properties and fibre volume fraction (see Table 1) without having voids in multidirectional laminates (see Figure 1) caused by the shrinkage behaviour of PP.



voids, $[\pm 45]_{2s}$ void-free, $[0/90]_{2s}$ and $[90]_8$

Figure 1. Microstructures for some lay-ups by applying different maximum pressure profiles.

Rectangular samples, 200 mm x 20 mm, were cut from the produced plates by a water-cooled diamond disc and 50 mm long tabs were prepared of $[\pm 45]_{2s}$ glass/PP laminates. Poor adhesion was obtained when using adhesives to bond the tab material onto the PP surfaces. Therefore, tabs are welded onto the glass/PP specimen by ultrasonic vibration welding.

Table 1: Plate properties for used maximum pressure and stacking sequences (five repetitions), selected consolidation pressure and properties are in bold

Stacking sequence	multidirectional		Unidirectional		
Applied pressure [bar]	35	**45**	40	35	**37**
density [g/cm^3]	1.69	**1.71**	1.74	1.69	**1.71**
(acc. ASTM B962)	± 0.02	± 0.03	± 0.01	± 0.01	± 0.01
fibre vol. [vol%]	-	**49.56**	51.01	49.01	**49.68**
(acc. ASTM D3171)		±0.48	± 0.56	±0.19	±0.24
microscopy	voids	void-free			

2.1 Testing methodology and details of crack detection by using 3D-DIC

All tensile tests are performed on a servo-hydraulic INSTRON 8801 with a load cell of ±100 kN using a testing speed of 2mm/min. All multidirectional laminates for the study of damage behaviour are tested up to 2.4 % axial strain, controlled by an extensometer. The final failure was avoided to allow matrix crack inspection after the experiment for validation purposes. In all experiments, strains are measured on the front surface by 3D-DIC that were later post-processed to obtain the axial stiffness reduction by using the secant modulus and Poisson's ratio evolution. The damage detection is performed on the polished edge surface by the second 3D-DIC system. An automated damage algorithm is developed to quantify matrix cracking based on the measured axial displacement field. Therefore, the post-processed axial displacement field by ViC-3D software is exported to the Matlab software for the crack detection approach. The criterion to define a crack in the off-axis ply is based on displacement discontinuities caused by the separation of crack surfaces [2]. Several crack detection paths are considered and equally spaced over the off-axis ply thickness to include also crack growth over the thickness. Post-mortem microscopic observations were performed after every single experiment by a Keyence microscope to identify cracks and to validate the crack detection algorithm to provide finally the crack progression during the performed tensile experiment.

3. Results and Discussions

3.1 Cross-ply $[0_2/90_2]_s$ laminate with embedded off-axis ply

The measured mechanical performance and average crack density evolution together with modelling results of $[0_2/90_2]_s$ glass/PP laminates are illustrated in Figure 2. In figure 2a) are the measured axial and transverse strains illustrated, in b) the evolution of Poisson's ratio and in c) the axial stiffness reduction versus the applied load for three samples, respectively. These results are measured by 3D-DIC on the front surface of every sample and validated by an attached extensometer. Excellent agreement is observed between both axial strain measurements. Very small scatter between the tensile performance of three samples can be seen, although in-plane fibre waviness cannot be denied for glass/PP. The detected cracks in the embedded 90 ply were obtained by performing 3D-DIC on the edge surface. An average crack density (Figure 2d) is used to consider the observed crack pattern (Figure 2e) by reporting the average of the crack numbers detected in every single path over the maximum crack distance. The majority of cracks are not fully propagated through the ply thickness caused by crack arresting phenomena due to localized matrix yielding in polymer-rich areas.

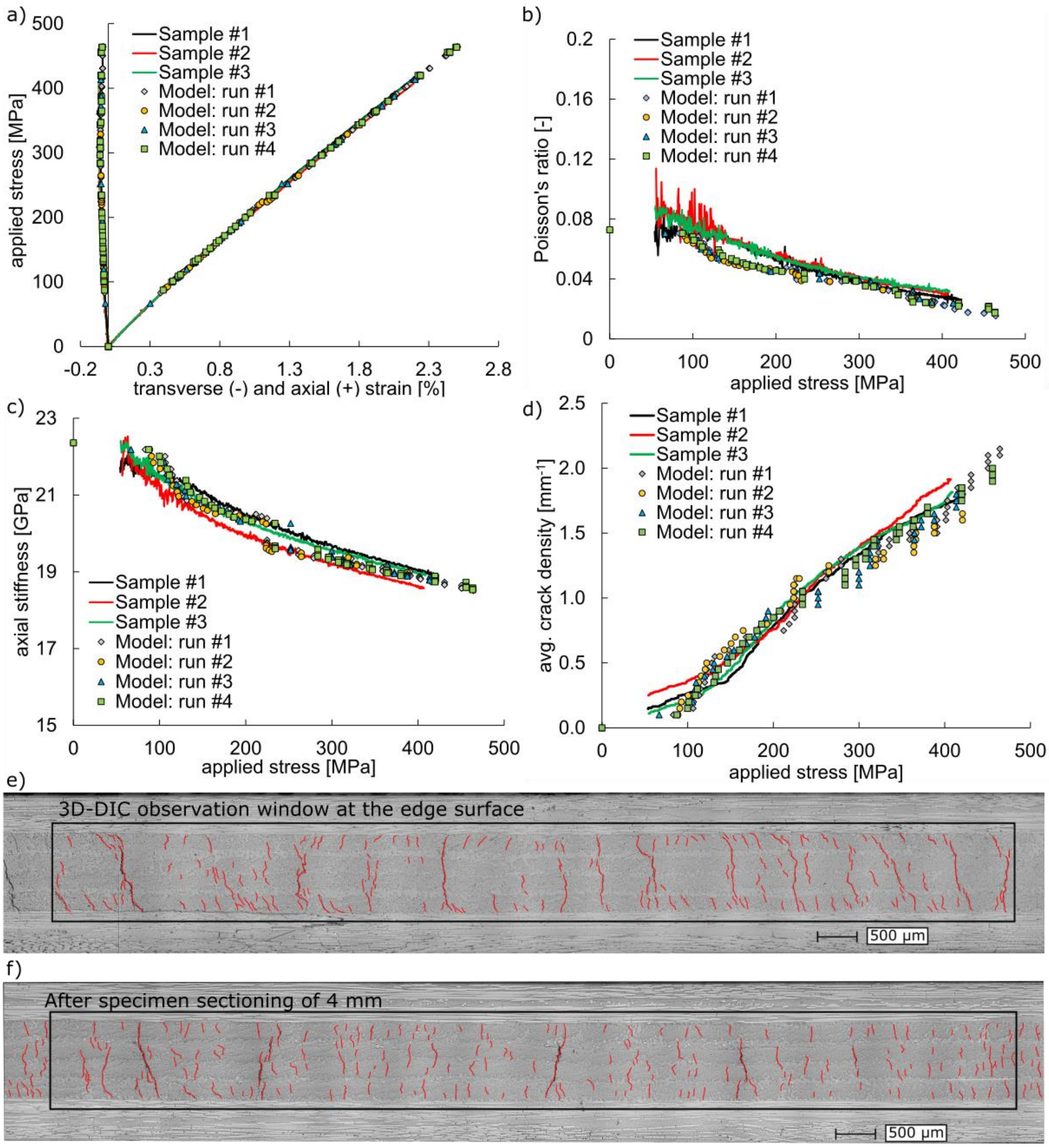


Figure 2. Quasi-static tensile behaviour of glass/PP $[0_2/90_2]_s$ laminate, measurements and modelling results. a) stress-strain performance, b) Poisson's ratio evolution, c) axial stiffness reduction, d) crack density evolution, microstructure after e) testing and f) sectioning

The first observation is that the model can be calibrated to predict a similar crack density growth as measured in the experiments for an average ply cracking fracture energy of 120 J/m^2 without consideration of residual stresses. This value is taken as a statistical value using a normal distribution with a standard deviation of 25% when performing four simulations using the variational approach [5]. Secondly, the model can accurately predict the axial and transverse strain evolutions while delivering very good predictions for the Poisson's ratio and axial stiffness reduction using the measured elastic material properties of E_{11} = 38.97 GPa, E_{22} = 5.39 GPa, G_{12} = 2.04 GPa and ν_{12} = 0.3 from testing basic laminates. Thus, when testing $[0]_8$ laminates, minor stiffness reduction of approx. 5% starting from 1 to 2 % axial strain was measured and included in the model. The latter observation confirms consistency between the observed damage modes, the reported average crack densities and a small amount of fibre breakage, and the measured laminate properties verifying the accuracy of both experiment and modelling. Finally, it is noteworthy that the observation of ply cracks is performed on the laminate edge surface and one might ask whether the same damage pattern exists inside the laminate. Sample sectioning by grinding and polishing over a depth of 4 mm from the edges was therefore performed (Figure 2f). The same number of cracks is observed as it was measured by 3D-DIC and manually counted in post-mortem microscopy before. However, due to the fibre waviness and matrix yielding effects, cracks are not exactly at the same location as before on the edge surface.

3.2 Cross-ply $[90_2/0_2]_s$ laminate with external off-axis ply

To observe crack propagation through the sample width, the $[90_2/0_2]_s$ cross-ply laminate is investigated with external 90 off-axis plies. The study of the results showed that an individual crack initiated at the edge and does not completely propagate through the sample width. However, there is almost always the same crack density measured at each considered detection path placed along the axial direction. This effect is mainly due to the presence of fibre waviness and polymer-rich areas inside the individual off-axis ply causing crack arresting by local matrix yielding, while there is another crack at a site very close by (Figure 3).

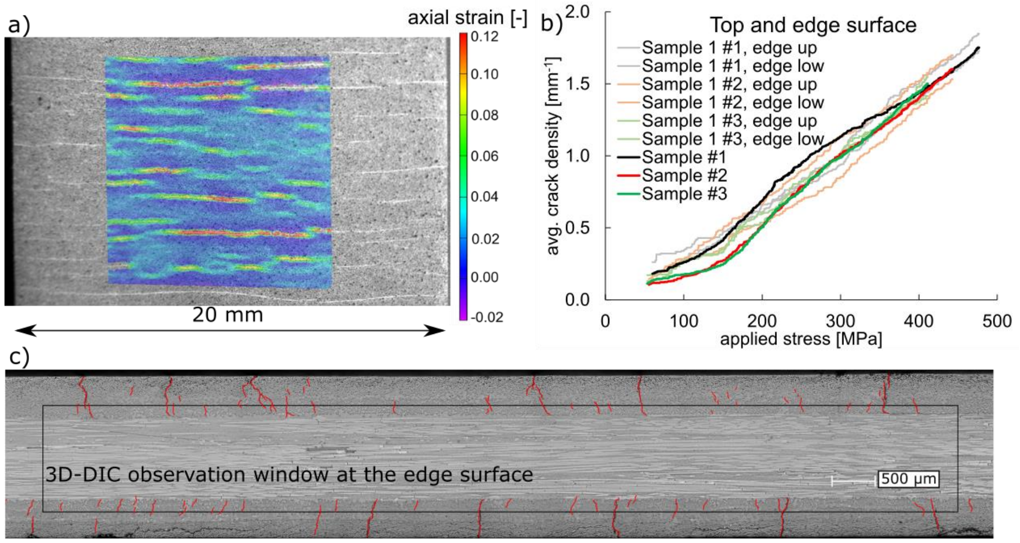


Figure 3. Crack detection on an externally attached 90 ply in a $[90_2/0_2]_s$ glass/PP laminate, a) axial strain map at 2.2 % global axial strain, b) comparison of average crack densities measured on the front and edge surface, c) damaged microstructure.

The mechanical performance and the detected average crack densities are in very good agreement between experiments and modelling using the same modelling inputs. The measured crack evolution on the top and the edge surface for the upper and lower 90 plies are very similar (Figure 3b). Although the 3D-DIC observation window (Fig. 3c) on the edge surface could only partially capture both 90 plies, no differences were observed by counting cracks manually.

3.3 $[0/45/0/-45]_s$ laminate with embedded 45 and -45 off-axis plies

The orientation of the off-axis plies can induce internal shear stresses which might affect the crack propagation. Figure 4 shows the mechanical performance (a-c), the measured average crack density evolution for the thick -45 ply (d) and the damaged microstructure after the test (e) and after sectioning (f). Cracks are present in both off-axis plies, but the thin 45 plies could not be fully captured by 3D-DIC and have been excluded from the measurements. The modelling has been performed using the same input material parameters as before. In summary, there is good agreement between the modelling and experimental results for both the effective mechanical properties and the microscopic matrix crack evolution. This states that although in the modelling, ply cracks are assumed to be fully propagated through the ply thickness, it has small effects on the effective laminate properties. Furthermore, the measured average crack density is a suitable parameter to characterize the damage extent.

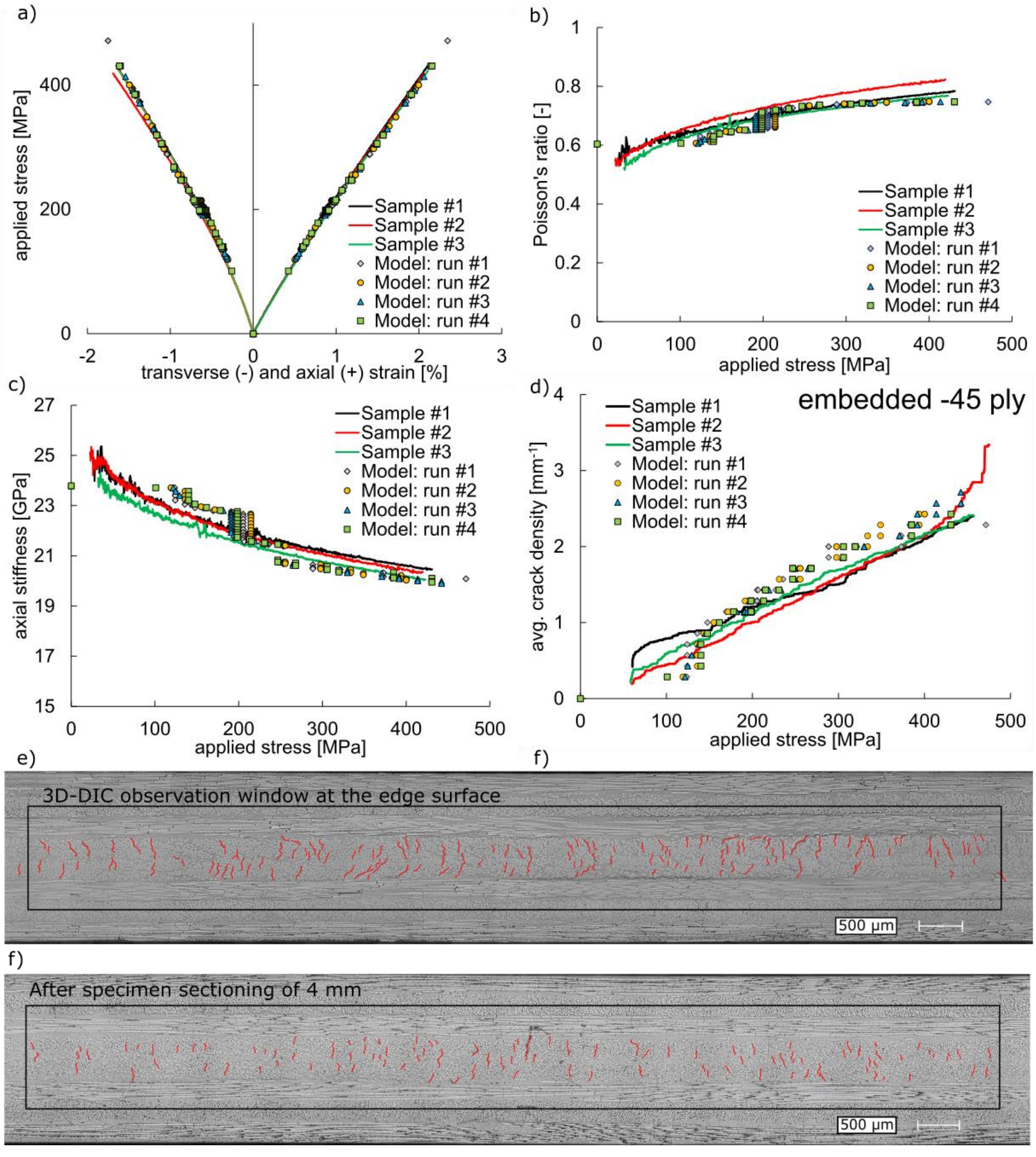


Figure 4. Quasi-static tensile behaviour of glass/PP [0/45/0/-45]$_s$ laminate, measurements and modelling results. a) stress-strain performance, b) Poisson's ratio evolution, c) axial stiffness reduction, d) crack density of -45 ply, microstructure after f) testing and g) sectioning.

3.4 Quasi-isotropic [0/45/90/-45]s laminate

It is useful now to characterize the mechanical behaviour of a more complex quasi-isotropic [0/45/90/-45]s laminate. Figure 5 shows the mechanical performance (a-c), the measured average crack density evolutions for -45 ply (d) and both 90 plies (e), the damaged microstructure after the test (g) and after sectioning (h).

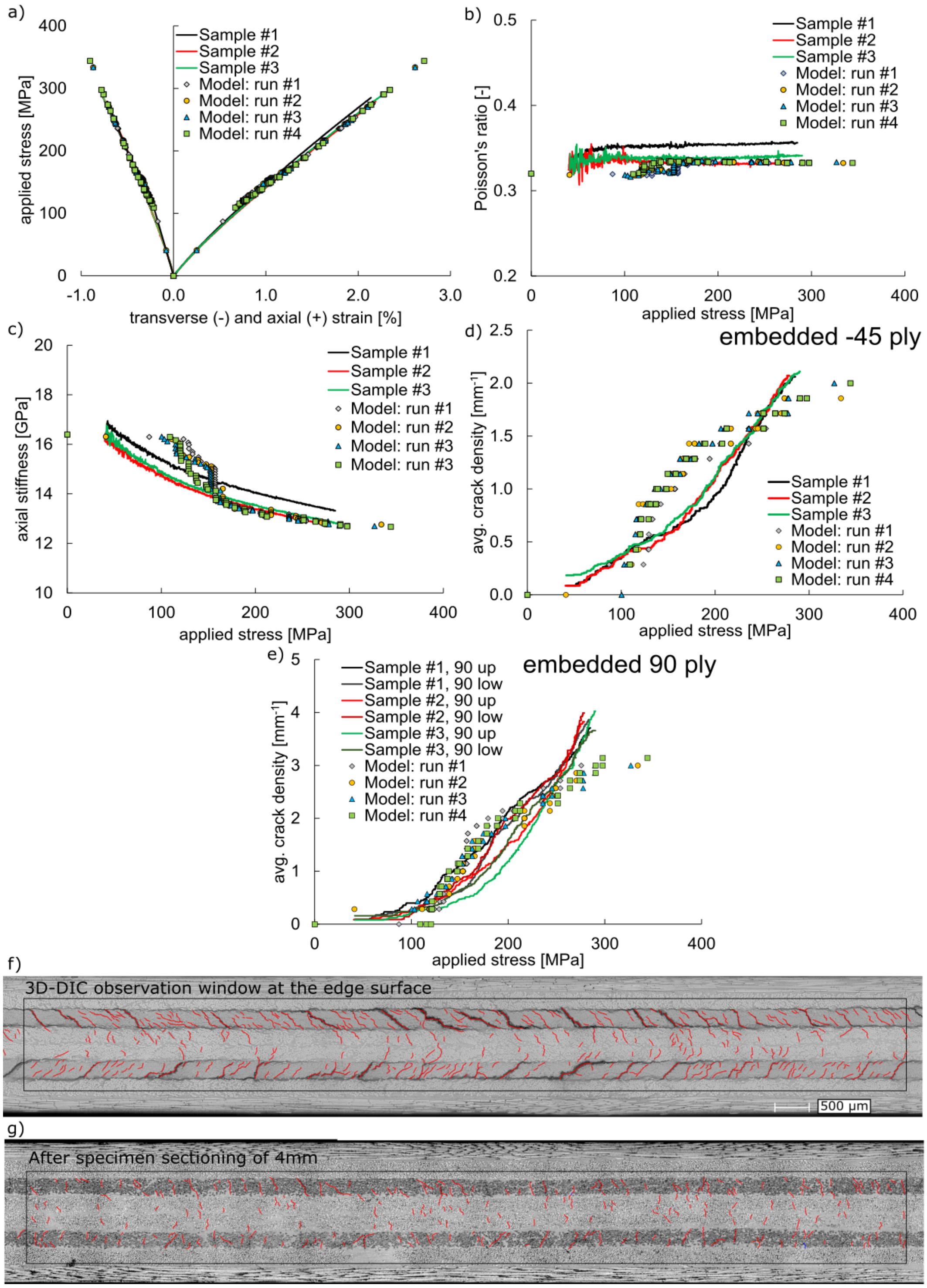


Figure 5. Quasi-static tensile behaviour of glass/PP [0/45/90/-45]s laminate, measurements and modelling results. a) stress-strain performance, b) Poisson's ratio evolution, c) axial stiffness reduction, crack density of d) -45 ply, e) both 90 plies, microstructure after f) test and g) sectioning

There is a rather good agreement between modelling and experimental results for the effective laminate properties but the crack densities are slightly over predicted. This can be explained by the assumption of fully propagated ply cracks through the thickness, while in reality more load is needed to propagate those cracks through the thickness. Another issue is that cracks in -45 ply are propagating under a mixed-mode condition and different oriented neighbouring plies as was the case previously. However, the same average fracture energy of 120 J/m^2 is assumed. The microscopic observations show that the entire interfaces of the 90 plies are delaminated and even some transverse cracks merged with delaminations (Fig. 5e) and caused large crack openings. Considering this aspect in the model requires measurements of the initiation and propagation of delaminations and the displacement opening of single cracks. The assumed average fracture energy of 120 J/m^2 can reasonably well predict the initiation and propagation of ply cracks in glass/PP off-axis plies and more importantly their effects on effective laminate properties for different lay-ups. Therefore, a physics-based damage modelling approach based on energy failure criteria can potentially predict the mechanical performance in the presence of different interactive damage mechanisms.

4. Conclusion

A novel instrumentation technique consisting of optical measurements by 3D-DIC is developed to measure quantitatively average crack densities in embedded and external off-axis plies including validations by microscopy for opaque multidirectional glass/PP laminate. The measured average number of cracks on the edge surface is validated by post mortem microscopy and sample sectioning confirmed the same number of cracks inside. The observed damage modes in multidirectional glass/PP laminates are in agreement with commonly reported damage modes, although localized matrix yielding and fabrication-induced fibre waviness influence the damage progression. Overall, a very good agreement between the experiments and modelling was obtained for all investigated multidirectional laminates by using the same modelling input parameters.

Acknowledgments

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5. References

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