ULTRASONIC POLAR SCAN IMAGING OF FATIGUED FIBER REINFORCED COMPOSITES

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Abstract
This study extends the use of both the amplitude and time-of-flight based pulsed ultrasonic polar scan (P-UPS) towards the inspection of damaged composite materials, more specifically fatigued carbon fabric reinforced thermoplastics (CETEX). The results demonstrate the excellent capability of the P-UPS method for nondestructively assessing and quantifying both shear-dominated and tension-tension fatigue damage in fabric reinforced plastics. The P-UPS results indicate that shear-dominated fatigued CETEX goes with a reduction of shear properties combined with large fiber distortions up to 13°. The P-UPS results of the tension-tension fatigued CETEX samples on the other hand reveal a directional degradation of the stiffness properties, reaching a maximum reduction of 12.8% along the loading direction. The P-UPS extracted damage characteristics are fully supported by simulations, conventional destructive tests as well as visual inspection.

1. Introduction

The excellent high-strength-to-low-mass ratio of fiber reinforced plastics, combined with their tunable elasticity and easy shaping of complex structures, makes them very interesting for use in high-tech applications demanding particular requirements, such as aerospace, wind turbines as well as others. Most often the mechanical nature of a composite material is anisotropic, demanding sophisticated inspection tools to affirm its design features, as well as to ascertain its mechanical and structural integrity during their life-time. The latter is of utmost importance considering that in-service components are subjected to a variety of loading conditions such as tensile, shear, fatigue and impact, effectively degrading the mechanical performance of the component. At present, ultrasonic detection of geometrical defects, such as delaminations and macro cracks, in fiber reinforced plastics is already well established [1; 2]. Basically the damaged area scatters the ultrasonic wave exposing the damaged area. Though, it is well known for fiber reinforced plastics that loading, and in particular fatigue loading, results in a directional reduction of elastic properties on the macro level through the initiation, progression and accumulation of micro defects [3; 4], thus requiring a more sophisticated NDT technique capable of quantifying a directional elasticity reduction.
The pulsed ultrasonic polar scan (P-UPS) technique [5] has already been demonstrated to be a promising means for NDT and material characterization. Basically, the method interrogates a

material spot with pulsed ultrasound from every possible angle of incidence $\psi(\varphi,\theta)$, with φ the azimuthal angle, further called the polar angle, and θ the angle with the normal on the surface, further called the incident angle (see Figure 1a). To enhance coupling of acoustical energy in the solid under investigation, water is used as immersion liquid. Simply mapping the transmitted (or if necessary the reflected) amplitude or its associated time of flight (TOF) of the ultrasonic pulse as a function of the incidence angle $\psi(\varphi,\theta)$ in a polar representation, yields a P-UPS image in which intriguing patterns can be observed (see Figure 1b). These characteristic contours put on view bulk wave characteristics, and consequently provide a fingerprint of the elasticity of the investigated material [6; 7; 8].

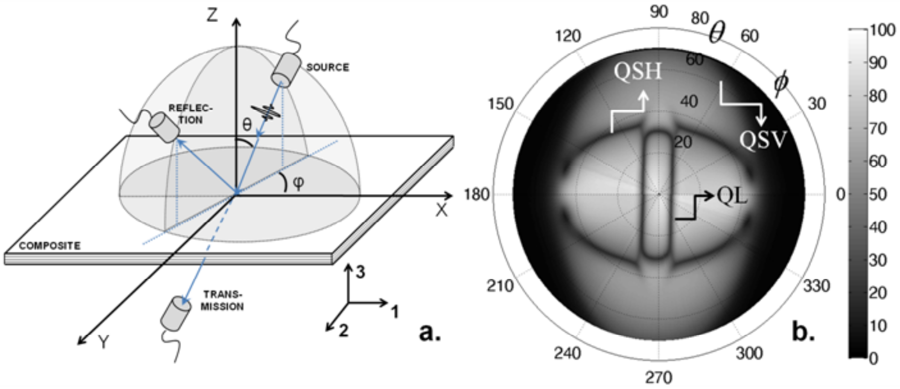

Figure 1: Schematic representation of the P-UPS principle (a) and amplitude based P-UPS for a $[0]_8$ C/E laminate (b). The indicators identify the characteristic P-UPS contours which reflect the material properties.

Early results obtained with the P-UPS technique include the detection of fiber direction [5; 6], determination of the fiber volume fraction [6] and the detection of different porosity levels [6]. More recently, the P-UPS has been successfully employed to characterize the elasticity tensor of orthotropic carbon fiber reinforced plastics [9]. In addition, (fiber reinforced) materials with degraded mechanical properties have also been investigated with the P-UPS technique. As such, P-UPS was proven a useful means for (i) detection of delaminations [10], (ii) the assessment of degradation induced by shear dominated quasi-static hysteresis loading (a small number of sequential loading-unloading cycles) on various fiber reinforced plastics [11], (iii) the semi-quantification of early stage (hidden) corrosion [12] and (iv) the detection and even localization of a (hidden) closed surface crack in a laminated glass panel [12]. Hence, it is clear that the P-UPS technique is a useful means for the inspection of various materials in different mechanical health. However, the application of the P-UPS technique for nondestructive detection and evaluation of fatigue damage in fiber-reinforced plastics has hardly been investigated. Most fiber-reinforced composites show a progressive directional reduction in stiffness properties upon fatigue loading through fiber/matrix interface debonding, matrix cracks, fiber bridging/pull-out/failure on the micro-scale [3; 4].
Where most of the existing NDT tools fail to assess the effect of fatigue damage in composites, the nature and design of the P-UPS method perfectly matches such kind of material degradation. This is exactly the scope of the current study: Does the P-UPS live up this promising capability of detection and evaluation of fatigue damage in composites?

2. Materials & Procedure

Several carbon fabric reinforced polyphenylene sulphide (PPS), called CETEX (Ten Cate, The Netherlands), have been subjected to dynamic fatigue loading, both in tensile and shear. The CETEX material is currently used as a structural component in the airbus A380. The fiber type is the carbon T300J 3K and the weaving pattern is a 5-harness satin weave with a mass per surface unit of 286 g/m^2. Tension-tension loading has been applied on two stacking sequences, $[+45°,-45°]_{4s}$ and $[(0°,90°)]_{4s}$, each having a total thickness of 2.5mm. Fatigue testing has been performed on a servohydraulic Instron 8800.

- The $[+45°,-45°]_{4s}$ sample is cut at a length of 250mm and a width of 30mm, and has been subjected to tension-tension loading at a frequency of 2Hz, which thus corresponds to shear-dominated fatigue. The fatigue loading, with shear stress range [0,50MPa], has been manually stopped after ±135000 cycles without fracture of the sample.
- Several $[0°,90°]_{4s}$ CETEX samples with a dumbbell shape have been prepared. Recently, it has been shown that this specific geometry shows an excellent performance during tension-tension fatigue for this specific material [13]. The specimens have been subjected to different tension-tension fatigue cycles at various load levels, until sudden failure of the specimens occurred:
  - Sample 1: 55 load cycles with stress range [0-700MPa] at a frequency of 2Hz
  - Sample 2: 314111 load cycles with stress range [0-625MPa] at a frequency of 5Hz

The specimens have been equipped with a clip-on extensometer and thermocouple. As such, the axial strain, load, actuator displacement and temperature have been measured simultaneously.
After applying the fatigue cycles, the sample has been demounted from the tensile machine and placed in the P-UPS setup. The scanner is equipped with two broadband unfocused piezoelectric transducers (General Electric), producing short bursts of ultrasound at a central frequency of $f_c = 2MHz$. This frequency has been selected based on the damping characteristics of the CETEX material. A higher central frequency is not advisable because this would lead to a largely reduced transmission characteristic, making the extraction of material features, and in extension the assessment of fatigue damage, more difficult. The angular range for the incident angle θ is at least [-65°,+65°], with a fixed resolution of 0.05°, while the range for the polar angle φ is set to [0°,180°] having an angular resolution of 0.5°. Hence, a single P-UPS experiment consists of around one million unique directions of insonification.

3. Results & Discussion

3.1. Simulation

The effect of a few material degradation phenomena, which are important for fatigued composites, on the P-UPS image is visually demonstrated in Figure 2 by means of P-UPS simulations. Figure 2a shows the P-UPS simulation considering viscoelastic material parameters which are representative for the CETEX material. The geometrical shape of the P-UPS image reflects the perfect orthotropic nature of the simulated $[0,90]_{4s}$ CETEX sample, i.e. the principal axes of orthotropy coincide with the fiber reinforcement structure. The simulation shown in Figure 2b represents a reduction of the stiffness E_1, resulting in a stretching of the inner square along $\varphi = 0°$. Figure 2c shows the simulation with a reduced in-plane shear modulus. Here, it is mostly the cross-shaped contour which is affected. Considering reduced shear properties in combination with a 8° distortion of the fiber orientation yields the simulation shown in Figure 2d. It can be observed that the inner square transformed to a rhombus, while the cross-shaped contour dropped several branches. Hence, the different material degradation features can be clearly discerned in the P-UPS simulations.

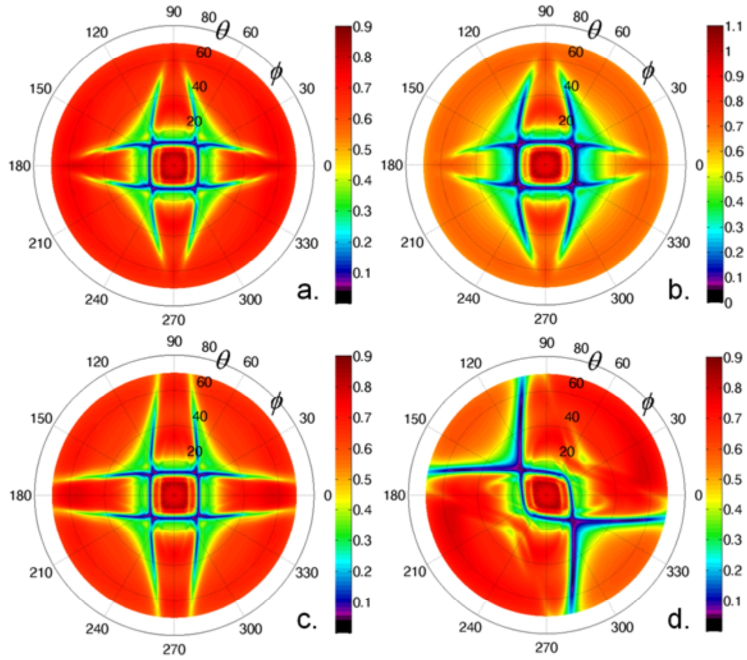

Figure 2: P-UPS simulation of CETEX with thickness 2.5mm at frequency f_c = 2MHz: virgin material (a), 30% reduction of E_1 (b), 30% reduction of G_{12} (c) and 30% reduction of G_{12} and 8° fiber distortion (d).

3.2 Experiment

3.2.1. Shear-dominated fatigue

The P-UPS results (amplitude and TOF) for the virgin $[+45,-45]_{4s}$ CETEX sample are presented in Figure 3. Apart from the 45° rotation, good correspondence is obtained with the simulation (see Figure 2a).

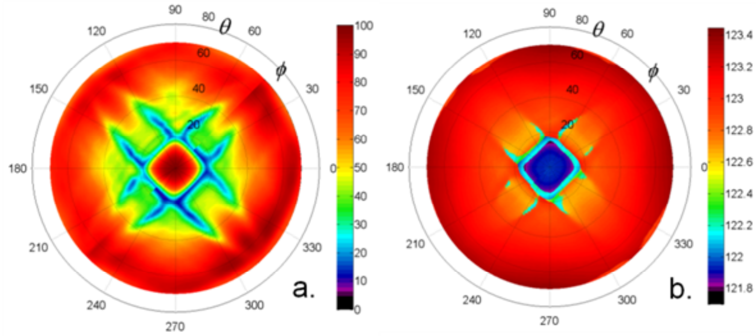

Figure 3: P-UPS result for virgin $[+45,-45]_{4s}$ CETEX fabric: amplitude (a) and TOF (b).

The $[+45,-45]_{4s}$ fabric has first been subjected to running-in load cycles: the desired shear stress level of 50MPa is achieved by cyclic loading and unloading at the frequency f = 2Hz while gradually increasing the tensile force (see Figure 4a). After this initiation process, the fatigue loading itself takes place until the test has been manually stopped after ±135000 load cycles without failure of the specimen. The variation in longitudinal strain ε_{xx}, as well as the temperature evolution during fatigue is shown in Figure 4b. The sudden temperature rise near the end of the fatigue loading originates from the internal friction of both multiple matrix cracks and overlapping fibers. Together with the temperature T, the longitudinal strain evolves in a similar way, which is a strong indicator that the material effectively underwent severe damage. A photograph of the specimen after fatigue loading is shown in Figure 4c, here necking of the specimen can be clearly observed. Both TOF and amplitude P-UPS have been obtained at three different spots, which basically can be categorized from little visual damage (A) over reasonable visual damage (B) to severe visual damage (C).

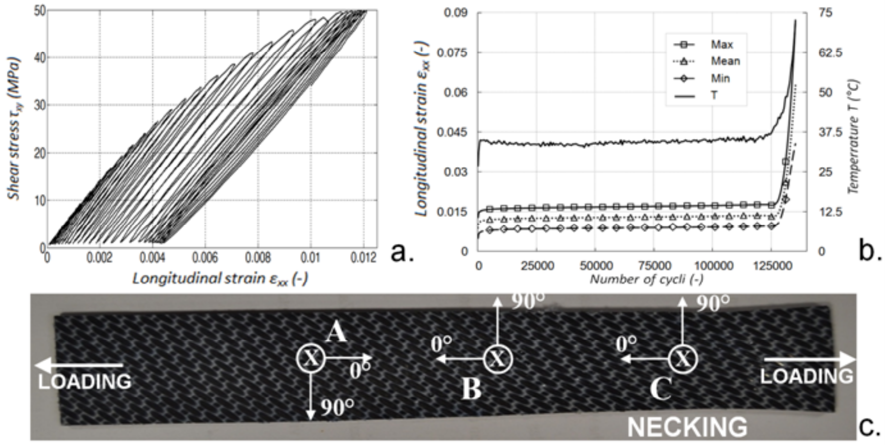

Figure 4: Running-in load cycles (a), evolution of longitudinal strain ε_{xx} and temperature *T* during fatigue loading (b) and photograph of shear dominated fatigued CETEX fabric (c). The labels denote the P-UPS scan locations, while the added coordinate systems coincide with the polar direction in the corresponding P-UPS image.

The P-UPS results for location A are displayed in Figure 5a-b. Contrary to the result of the virgin CETEX sample (see Figure 3), the inner QL-contour is not a square anymore, but has rhomboid features indicating a distortion of the fiber orientation [11]. Extraction of the angular orientation of the inner contour lines provides the global fiber direction of the sample (added to Table 1). In addition, the amplitude recorded P-UPS reveals that the cross-like contour, which is connected to the shear properties, is subjected to both a shortening and lengthening of its branches. This indicates that the initially perfect orthotropic material locally transformed to a lower symmetry class.

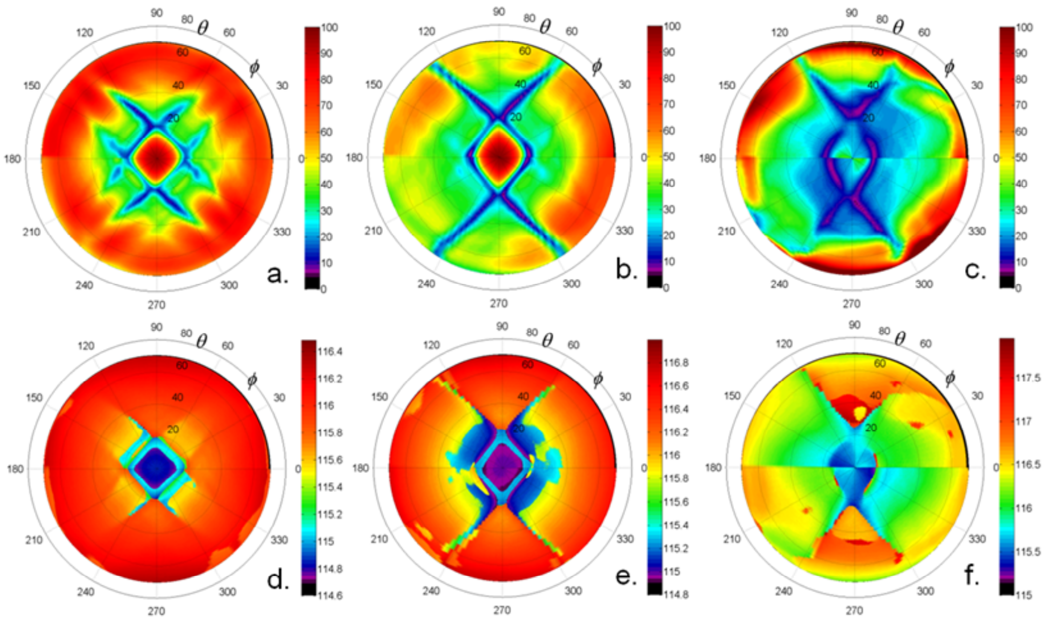

Figure 5: P-UPS results for a shear dominated fatigued $[+45,-45]_{4s}$ CETEX fabric: amplitude recording (top row) and TOF recording (bottom row). Material spot A (a-d), material spot B (b-e) and material spot C (c-f).

These indicators become even more outspoken at scan location B, both in the amplitude and the TOF recording (Figure 5e-f). The inner contour now clearly transformed its shape to the class of rhombi, a fiber distortion of 8° has been extracted (see Table 1). The original cross-like contour changed its topology to 4 symmetric branches. Note the good agreement with the

numerical result (of course rotated over 45°) displayed in Figure 2d. It is further noted that the time scale of the TOF recorded P-UPS spans a larger range. In other words, in some material directions, the ultrasonic signal needs more time to traverse the sample, and thus propagates at a lower rate. Obviously, this is an additional indicator of the presence of material damage.
Finally, the most heavily damaged spot (C) is investigated. The distortion of the local fiber orientation becomes even worse, and reaches a maximum rotation of more or less 13° (see Table 1). With X-ray, fiber distortions in the same order of magnitude have already been measured for composites, although loaded in a quasi-static shear state [14]. Note that the extracted distortion is on average since each layer has its own distortion level. The appearance of such large fiber distortions can be understood by realizing that the CETEX material belongs to the class of thermoplastic composites. Hence, the temperature rise during cyclic loading (see Figure 4b) brings the PPS matrix close to its softening temperature ($T_g \approx 85°C$), making it relatively easy for the fibers to realign upon loading. For similar composites, we have measured temperatures up to 110°C at the necking area. Since the surface of the sample is marked with a characteristic pattern (see Figure 4c), we also determined optically the local fiber distortion of the outer layers. However, note that the optically determined values are only valid for the outer layers, and thus could deviate from the actual internal fiber distribution. The amplitude recorded P-UPS further shows that the transmission field drops in amplitude level for small incident angles ($\theta < 20°$). This is most probably related to scattering of quasi-longitudinally polarized waves on damage related geometrical discontinuities [11]. The TOF result reveals a further increase of the range of the time scale. Note that the increased travel time mainly manifests itself in certain material orientations, accentuating the directional nature of the fatigue damage.

Scan Location	Virgin	A	B	C
P-UPS	-45° +45°	-40 (+5) +42 (-3)	-37° (+8°) +37° (-8°)	-31° (+14°) +34° (-11°)
Optical	-45° +45°	-41° (+4°) +42° (-3°)	-38° (+7°) +38° (-7°)	-33° (+12°) +36° (-9°)

Table 1: Ultrasonically and optically extracted local fiber orientation for the $[+45,-45]_{4s}$ CETEX fabric subjected to shear-dominated fatigue loading.

3.2.2 Tension-tension fatigue

In analogy with previous paragraph, the influence of fatigue on the P-UPS image is investigated, but now for the CETEX sample with the $[0,90]_{4s}$ stacking sequence. The P-UPS image for a virgin $[0,90]_{4s}$ CETEX sample obviously corresponds to the P-UPS results of the virgin $[+45,-45]_{4s}$ CETEX sample, but rotated over an angle $\varphi = 45°$. In the 0°-direction, respectively 90°-direction, the inner contour is positioned at $\theta = 13.88°$, respectively $\theta = 13.57°$. This correspond to a stiffness of E_{xx} = 54GPa and E_{yy} = 57GPa, which is in close agreement with literature [3]. The deviation between both stiffness values is a result of the difference in pre-stress between warp and weft yarns during the weaving process. The P-UPS results of the shear dominated specimen revealed the spatial distribution of fatigue damage (see Figure 5), thus P-UPS scans are ideally performed at that spot where maximum material degradation occurred, obviously being the fractured region. However, this is not recommended because geometrical discontinuities near the failed zone would obviously influence the P-UPS image, making a straightforward interpretation in terms of a reduction of material stiffness difficult. Therefore, the insonification spot is chosen at a distance of $d \approx 15$ mm from the failed zone in order to avoid any 'edge' effects in the P-UPS image.

Due to the high applied stress level (90% of the ultimate tensile strength), sample 1 withstood only 55 load cycles before failing and thus underwent low-cycle fatigue. Apart from a slight drop in transmitted amplitude, which can be attributed to the scattering of the ultrasonic waves on multiple matrix cracks and material clusters, a slight directional stretching of the polar contours can be observed as observed in the simulation shown in Figure 2b. Notwithstanding the very limited number of load cycles, a small stiffness reduction along the loading direction is obtained as could be expected for the CETEX material [3; 13]. A reduction of 3.7% for the stiffness along the loading direction is determined, while the stiffness modulus transverse to the loading direction remains more or less constant.

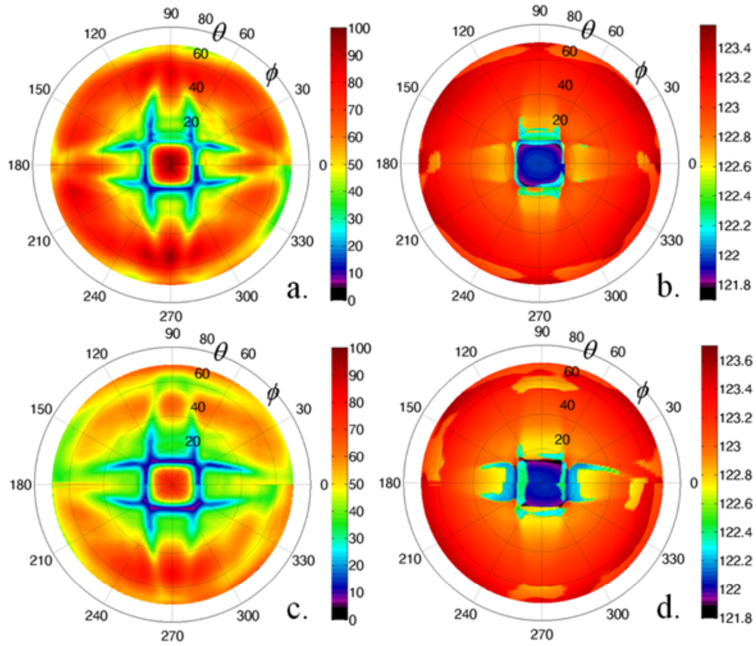

Figure 6: Amplitude (left colum) and TOF (right column) based P-UPS results for tension-tension fatigued CETEX fabric: sample 1 (a-b), sample 2 (c-d).

The P-UPS results of sample 2 show a more pronounced stretching of the inner contour (see Figure 6c-d), indicating a larger reduction of stiffness properties. A reduction of 12.8%, for the stiffness along the loading direction has been extracted. Again the stiffness transverse to the loading direction remains more or less constant, affirming the directional nature of the tension-tension fatigue damage. The extracted stiffness reduction is in full agreement with earlier observations reported in [3], where it was shown that the stress-strain response of the $[0°,90°]_{4s}$ laminate after high-cycle fatigue is nonlinear, showing a considerably lower stiffness for small strains, and a much higher stiffness for high strains. This is due to the geometrical stiffening of the laminate: due to the fatigue damage, the warp yarns are delaminated from the surrounding matrix and weft yarns, and can straighten up when tensile loading is applied. In case of ultrasonic inspection, the applied mechanical strains are negligible, so the stiffness is measured in the small-strain regime. In addition, sample 2 was provided with an extensometer, from which a stiffness reduction of ~11% has been extracted (in the small-strain regime) which is in good agreement with the P-UPS data.

4. Conclusions

The potential of the P-UPS methodology for inspection and evaluation of fatigue in fabric reinforced plastics has been demonstrated, both numerically and experimentally. Several CETEX samples, subjected to either shear-dominated or tension-tension fatigue at various load levels, are investigated at multiple material spots with the P-UPS technique in order to assess fatigue damage.

The P-UPS results for the CETEX sample fatigued in a shear-dominated regime reveal fiber distortions up to 13°. On the basis of this result, one could actually question whether damage simulation models should be extended to account for fiber distortion and in extension for a transformation in mechanical symmetry class. The P-UPS results for the tension-tension fatigued CETEX samples reveal a reduction of stiffness up to 12.8% along the loading direction, confirming the directional nature of damage associated to tension-tension fatigue.

Overall, good correspondence is obtained with simulations, conventional destructive tests, visual inspection as well as literature, indicating the excellent feasibility of the P-UPS technique to monitor and evaluate fatigue damage in fabric reinforced composites.

References

[1] P.R. Armitage, C.D. Wright, Design, development and testing of multi-functional non-linear ultrasonic instrumentation for the detection of defects and damage in CFRP materials and structures. Composites Science and Technology 87 (2013) 149-156.

[2] S. Yashiro, J. Takatsubo, N. Toyama, An NDT technique for composite structures using visualized Lamb-wave propagation. Composites Science and Technology 67 (2007) 3202-3208.

[3] S. Daggumati, I. De Baere, W. Van Paepegem, J. Degrieck, J. Xu, S.V. Lomov, I. Verpoest, Fatigue and post-fatigue stress-strain analysis of a 5-harness satin weave carbon fibre reinforced composite. Composites Science and Technology 74 (2013) 20-27.

[4] S. Giancane, F.W. Panella, V. Dattoma, Characterization of fatigue damage in long fiber epoxy composite laminates. International Journal of Fatigue 32 (2010) 46-53.

[5] W.H.M. Vandreumel, J.L. Speijer, Non-destructive composite laminate characterization by means of ultrasonic polar-scan. Materials Evaluation 39 (1981) 922-925.

[6] J. Degrieck, N.F. Declercq, O. Leroy, Ultrasonic polar scans as a possible means of non-destructive testing and characterisation of composite plates. Insight 45 (2003) 196-201.

[7] M. Kersemans, W. Van Paepegem, K. Van Den Abeele, L. Pyl, F. Zastavnik, H. Sol, J. Degrieck, Efficient Extraction of the Directional Wave Curves from a Pulsed Ultrasonic Polar Scan Experiment, in: J. Grum, T. Kek, (Eds.), Proceedings of the 12th International Conference for Non-Destructive Testing 2013 (ICNDT2013), Portoroz, Slovenia, 2013.

[8] N.F. Declercq, J. Degrieck, O. Leroy, Simulations of harmonic and pulsed ultrasonic polar scans. Ndt & E International 39 (2006) 205-216.

[9] M. Kersemans, A. Martens, N. Lammens, K. Van Den Abeele, J. Degrieck, F. Zastavnik, L. Pyl, H. Sol, W. Van Paepegem, Identification of the elastic properties of isotropic and orthotropic thin-plate materials with the pulsed ultrasonic polar scan. Experimental Mechanics IN Press DOI: 10.1007/s11340-014-9861-7 (2014).

[10] M. Kersemans, A. Martens, K. Van Den Abeele, J. Degrieck, L. Pyl, F. Zastavnik, H. Sol, W. Van Paepegem, Detection and localization of delaminations in thin carbon fiber reinforced composites with the ultrasonic polar scan. Submitted to Journal of Nondestructive Evaluation (2014).

[11] M. Kersemans, I. De Baere, J. Degrieck, K. Van Den Abeele, L. Pyl, F. Zastavnik, H. Sol, W. Van Paepegem, Nondestructive damage assessment in fiber reinforced composites with the pulsed ultrasonic polar scan. Polymer Testing 34 (2014) 85-96.

[12] M. Kersemans, W. Van Paepegem, K. Van Den Abeele, L. Pyl, F. Zastavnik, H. Sol, J. Degrieck, The pulsed ultrasonic backscatter polar scan and its applications for NDT and material characterization. Experimental Mechanics In Press DOI: 10.1007/s11340-013-9843-1 (2014).

[13] I. De Baere, W. Van Paepegem, C. Hochard, J. Degrieck, On the tension-tension fatigue behaviour of a carbon reinforced thermoplastic part II: Evaluation of a dumbbell-shaped specimen. Polymer Testing 30 (2011) 663-672.

[14] F. Sket, A. Enfedaque, C. Alton, C. González, J.M. Molina-Aldareguia, J. Llorca, Automatic quantification of matrix cracking and fiber rotation by X-ray computed tomography in shear-deformed carbon fiber-reinforced laminates. Composites Science and Technology 90 (2014) 129-138.