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A FRACTOGRAPHIC ANALYSIS OF DELAMINATION RESISTANCE OF LAMINATES WITH FABRIC REINFORCEMENT

The combined fractographic and simple stress analysis showed that there are several mechanisms responsible for a relatively high delamination resistance of laminates reinforced with fabrics. It was concluded that they result from yarn weaves and curvatures produced in the course of weaving.

1. Introduction

Delamination is a fracture process specific to materials of lamellar structure. It results in separation of one or more layers from the parent body and is considered as the main cause of laminate structure failure. For this reason, the delamination process gains a lot of attention. The majority of the publications on fractographic delamination investigations focus on the laminates with UD reinforcement, in which delamination mechanisms are relatively simple. There is a shortage, however, of the papers on fractographic delamination investigations occurring in laminates reinforced with fabrics and the micromechanisms responsible for relatively high delamination resistance of such laminates need further research. The investigations objective was to provide the background for relatively high critical values of delamination resistance revealed by laminates reinforced with fabrics as well as to explain apparent contradictions related to the local fracture appearance and global loading modes. The investigated laminates are composed of fabrics made with E glass (INTERGLAS 92145 and 92125) and epoxy resin Ep 52. The fabric weaves are shown in Fig. 1.

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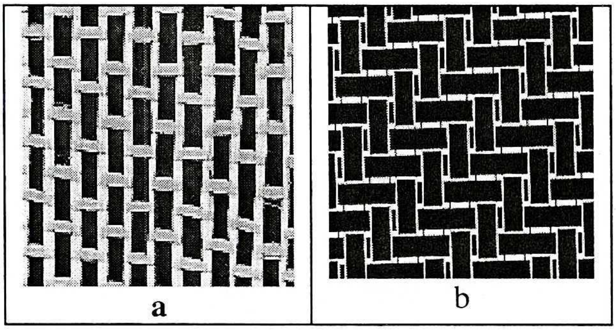


Fig. 1. Considered fabric reinforcements: a) INTERGLAS 92145 unidirectional fabric, (UD), b) INTERGLAS 92125 2x2 twill fabric (symmetric)

Such reinforcement is easy to handle. It also allows maintaining the mechanical properties of laminates on reasonable level and for these reasons is widely used in various industries. In a case of fabric reinforcement, characteristic feature of the delamination process consists in the fact that the general fracture plane located at the boundary between the layers maintains its initial interlaminar location during entire delamination process. The experimental results indicate that for the same composite systems, (i.e. the same glass fibre, fibre surface preparation and resin-hardener system), tested under the same conditions, resistance to delamination varies with the loading modes and arrangement of reinforcement, Fig. 2.

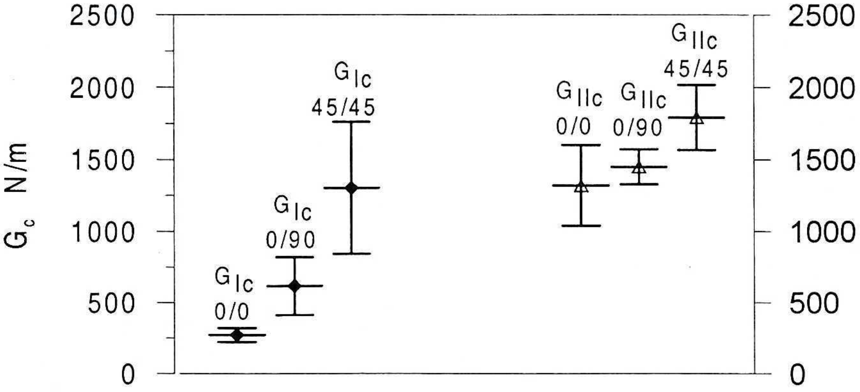


Fig. 2. Critical values of the Strain Energy Release Rate for Mode I, (Double Cantilever Beam test), and Mode II, (End-Notched Flexure test), loadings for three different reinforcement arrangements: 0/0 – reinforcement parallel to the direction of crack propagation; 0/90 – symmetric fabric, (2x2 twill), the warp parallel and the weft perpendicular relatively to the direction of crack propagation; 45/45 – warp and weft rotated through 45° with the respect to the direction of crack propagation

For Mode I and Mode II loadings, the lowest resistance against the delamination is revealed by the laminates composed of layers of unidirectional reinforcement arranged in the direction of crack propagation (0/0). The fabric reinforcement, (2×2 twill), with the weft and warp parallel and perpendicular to the crack propagation direction, (0/90) enhances significantly delamination resistance. Rotation of weft and warp through 45° results in even higher resistance. To explain these differences, the fracture surfaces representative of each case described were examined with the use of SEM. In the case of 0/0 reinforcement arrangement it is possible to distinguish simple surface features being characteristic for each mode of loading. To be referred to throughout the paper, these features and mechanism of their formation are described in Section 2 of the paper.

In the case of 0/90 and 45/45 reinforcement arrangements, more complex surface forms composed of the simple ones described in the first section are present. The formation of complex fracture surface forms generates large new area and results in the increase of the delamination resistance.

In the certain fracture areas, the surface features present do not correspond to the global, (remote) loading mode. The reasons for that are explained with the help of the simple stress analysis in Section 3 of this paper.

2. Simple forms of a fracture surface resulting from Mode I, Mode II and Mixed-Mode I/II loadings. Unidirectional reinforcement parallel to the general direction of crack propagation

Simple forms of a fracture surface, Figs. 3, 5 and 6 resulting from Mode I, Mode II and Mixed-Mode I/II tests, respectively, can be easily distinguished in delaminated laminates reinforced with UD fabrics. (The tests were carried out by the author with the use of the Double Cantilever Beam, End-Notched Flexure and Mixed-Mode Bending specimens, [1], respectively). It is commonly accepted that non modified typical epoxy resin breaks in a brittle manner due to normal stress, and the resulting fracture surface is perpendicular to the principal tensile stress.

The most important features of the fracture surface resulting from global Mode I consist in relatively smooth fracture surfaces of the resin between bare fibres being almost totally separated from the surrounding resin, Fig. 3.

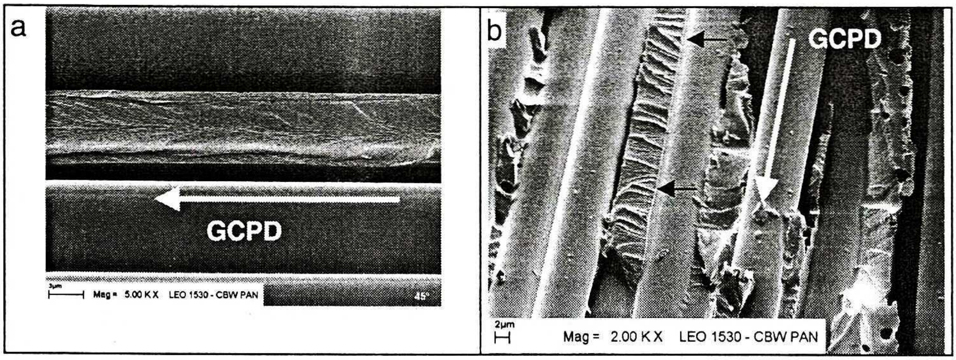


Fig. 3. Features of the delamination surface due to Mode I loading. a) bare fibres separated from the resin matrix and relatively smooth surface of the fractured resin b) "river pattern" characteristic for the local transverse crack propagation in resin [2], prior to the complete separation of fibres from resin. Also, fibre prints left by broken, puled out fibres are clearly visible

The separation of fibres from the resin results from relatively weak interface and the stress state existing prior to the separation. The results of the FE analysis, Fig. 5, indicate that at the fibre-matrix boundary the radial stress is present. For the local plain strain conditions the radial stress is tensile at whole circumference of a fibre, for the local plain stress condition the radial stress becomes compressive along small circumference section. This compressive stress and (or) local random increase in interface strength can possibly prevent simultaneous separation of fibres from matrix along whole fibre circumference. Under such conditions, crack locally propagates in the resin in the direction perpendicular to the fibre axis from one fibre to another leaving the characteristic "river marks" that indicate the local direction of crack propagation, Fig. 3b.

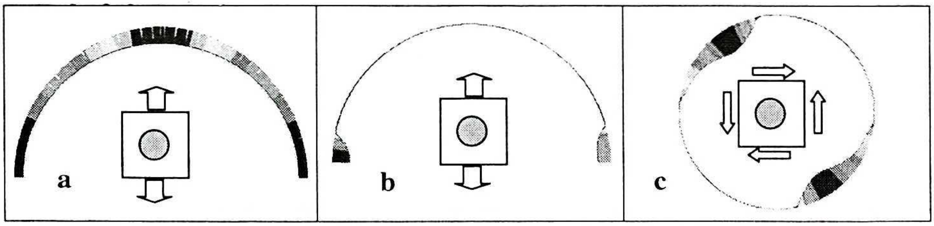
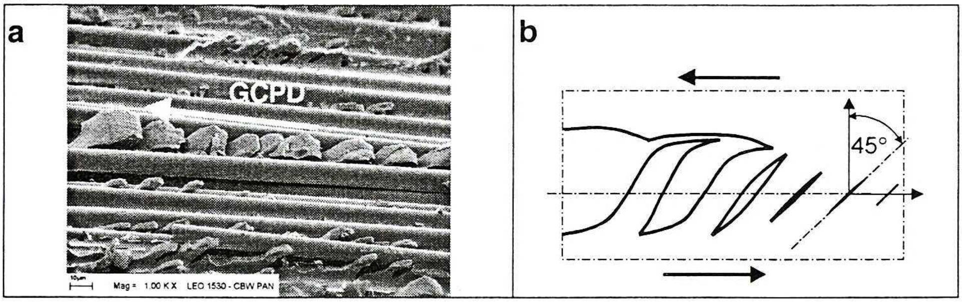


Fig. 4. Distribution of radial stress along fibre circumference at the fibre-matrix boundary for global Mode I and Mode II loadings. Stress outside the circle is positive and inside the circle is negative; a – local plain strain state conditions, b – local plane stress state conditions, c – for global Mode II loading

Figure 5 shows the fracture surface produced by global Mode II loading. The most characteristic features that allow finding the difference between the fractures resulting from Mode I and Mode II loading are sigmoid hackles protruding from the fractured resin cross-section located between bare fibres, [2], [3]. The sketch shown in Fig. 5b explains the mechanism of the hackle formation, [4].



Rys. 5. Fracture surface features resulting from the global Mode II loading. Sigmoid hackles protruding from the broken resin section located between fires are clearly visible; b) formation mechanism – hackles are produced by the principal tensile stress corresponding to the shear stress resulting from the global Mode II loading, [4].

Pictures in Fig. 6 show the fracture surfaces resulting from Mixed-Mode I/II loading. The values of (Mode I / Mode II) ratio increase from left to right. This variation is reflected by the appearance of the fractures. All the pictures were taken from the same direction, and clearly show changes in the tilt of hackles resulting from the changes in orientation of the principal tensile stress. It can be also seen that the number of hackles decreases as the (Mode I/Mode II) ratio increases.

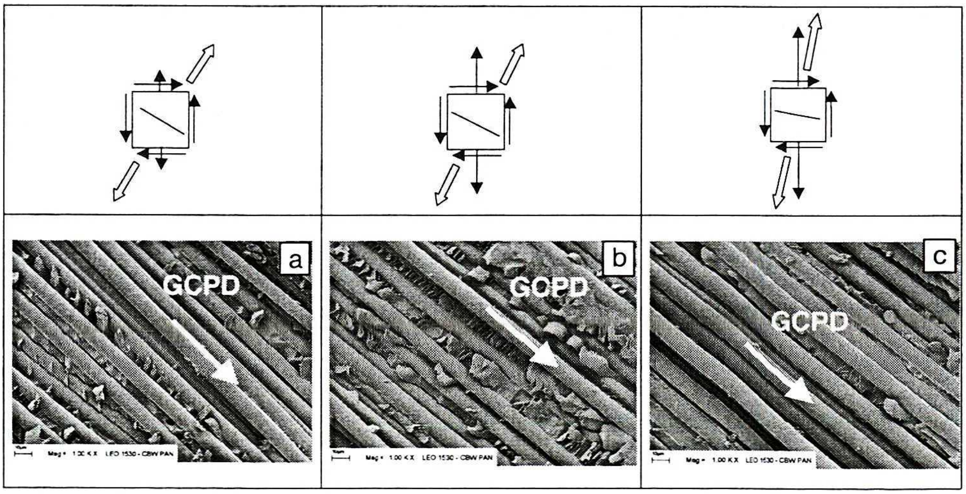


Fig. 6. Changes in morphology of the fracture surfaces resulting from variation in the (Mode I/Mode II) ratio: a) I/II = 0.3, b) I/II = 1, c) I/II = 4.

The above remarks can be summarised as follows. Due to relatively weak interface and the local stress state, the matrix and fibres separate from each other. This results in reduction of cross section area that can transfer load to the narrow strips of matrix of varying cross sections that fill the space between fibres. The matrix fails at the cross sections perpendicular to the principle tensile stress and approximately parallel to the fibre axes. Depending on the orientation of fibres relative to the principle tensile stress, the matrix fractures remains plane (Mode I loading) or display hackles, (Mode II loading). The number of hackles varies with the (Mode I/Mode II) ratio. The presence of hackles increases the fracture area, which results in the increase of toughness.

3. Forms of fracture surface in delaminated laminates reinforced with 2×2 twill fabric

To explain relatively high delamination resistance of laminates reinforced with symmetric fabrics, one should analyse the mechanisms involved in fracture process on three different levels: macro, meso and micro and of characteristic dimensions such as width of delamination, width of a reinforcement yarn, and diameter of a fibre, respectively. Mechanisms acting on micro level are the same as described above.

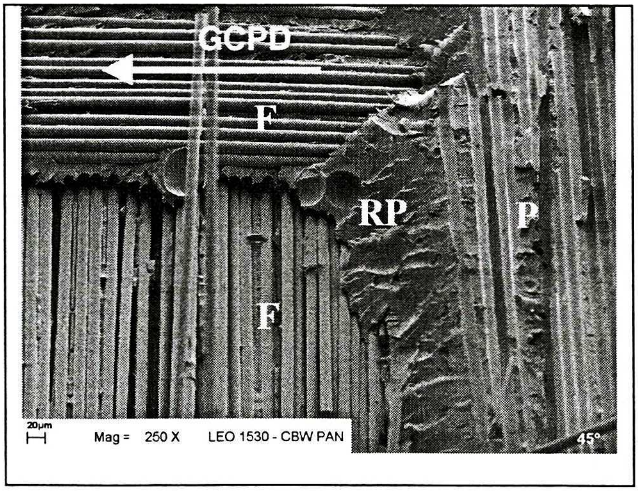
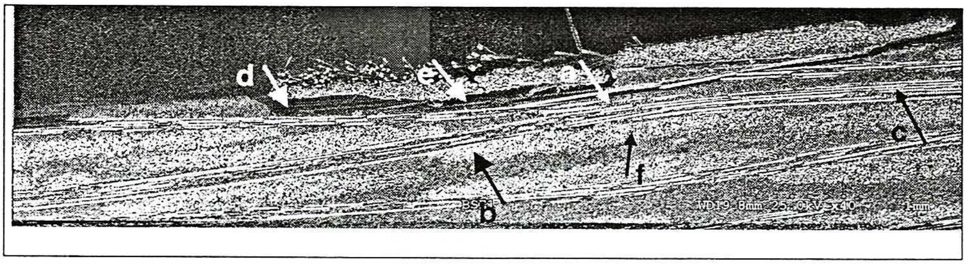


Fig. 7. Yarn crossing. RP – resin pocket, P – fibre prints, F – bare fibres

On the macro level, a crack develops between the adjoining reinforcement layers maintaining its initial location. In general, its path reflects the yarn curvatures, however in a case of brittle matrix it also takes advantage of the resin pockets located next to yarn crossings and passes through them, Fig. 9, to make the path shorter. It makes the fracture surface larger comparing to that generated in the case of UD reinforcement, however, it is not the main cause of the observed high delamination resistance.

The main cause results from the meso level fracture mechanisms. These mechanisms are due to weaves and the yarn curvatures produced in the course of weaving.



Rys. 8. Meso level features of intralayer fracture; a-crack between two parallel yarns, transverse to GCPD, b – crack between yarns perpendicular to each other, c – crack at the resin – yarn boundary, d – crack separating every single fibre, e – intrayarn crack in the transverse yarn, f – intrayarn crack in the yarn parallel to the GCPD.

Yarns weaving decreases structural homogeneity and enhances intrayarn fracture, separation of single fibres at yarn boundaries and separation of yarns inside the same layer of fabric, Fig. 8. It is worthy to notice that the yarns parallel to the general crack propagation direction, (GCPD), usually do not allow crack to cross them because of their high strength forcing the crack to go back and forth inside one or another fabric reinforcement layer being separated by the delamination, [5].

Close examination of certain fracture regions, Fig. 9, reveals the features not corresponding to the global loading modes. In the case of global Mode I loading, one can distinguish the regions displaying features unique for the Mode II and Mixed-Mode I/II loadings, Fig. 10, and in the case of the global Mode II loading the regions displaying features representative for the Mode I and Mixed-Mode I/II loadings, Figs. 11 end 12. This apparent contradiction can be explained with the help of a combine simple stress and fracture topographies analysis. Since the crack partially envelops the yarns, the fibres at the periphery of the yarns are separated from the matrix first of all. As it was mentioned in the previous section, as a result only relatively narrow blocks of matrix between the fibres can take over the load. If their cross section areas perpendicular to the principle tensile stress are not sufficient the matrix fails. Due to the weaving process, all the yarns curve and their cross sections become elliptic. Therefore, the stress state determined at the surface enveloping the yarns varies with location according to the local orientation of a normal.

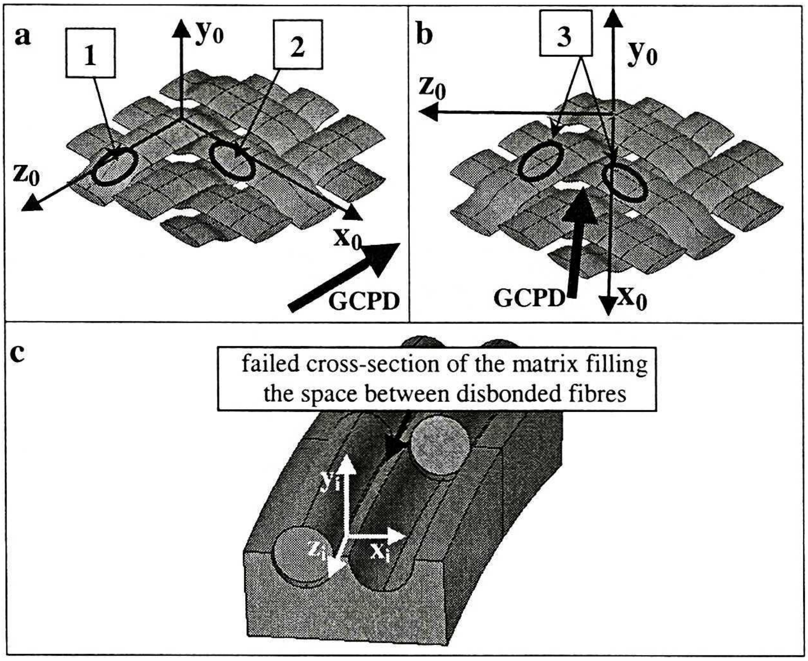


Fig. 9. Analised regions of the fractures: a – for 0/90 arrangement , b – for 45/45 arrangement; c – enlargement of the local failure locus; the axis y_0 is parallel to the local direction of the normal to the matrix cross-section most vulnerable to failure

The global, (remote) stress state is defined in the global co-ordinate system $x_0y_0z_0$ and denoted as σ_y and τ_{xy} for Mode I and Mode II loadings respectively. The stress state in the local co-ordinate system is given by the transformation rule (1)

$$\sigma'_{kl} = \sigma_{ij}\, a_{kj}\, a_{li} \tag{1}$$

where:

Table 1

	$x_1 \equiv x_0$	$x_2 \equiv y_0$	$x_3 \equiv z_0$
$x'_1 \equiv x_m$	a_{11}	a_{12}	a_{13}
$x'_2 \equiv y_m$	a_{21}	a_{22}	a_{23}
$x'_3 \equiv z_m$	a_{31}	a_{32}	a_{33}

$m = 1,2$

For the global Mode I loading, in the slop area 1, Fig. 9a, the fibres next to the yarn boundary are approximately parallel to plane x_1z_1 defined in the co ordinate system $x_1\ y_1\ z_1$, for which the values of a_{ij} are given in Table 2. The matrix cross sections bounded on both sides by the closest generating lines of adjacent fibre are approximately of the same orientation. These cross sections are most vulnerable to failure due to their small with. Stress σ_y corresponding to the global Mode I loading, transformed to $x_1\ y_1\ z_1$ co ordinate system in this new co ordinate system is equivalent to the combination of shear and normal stresses. This stress state corresponds to the Mixed Mode I/II loading and produces fracture forms corresponding to this loading mode, see Figs 5 and 10, and for $a_{11} = \frac{\sqrt{2}}{2}$, ($\varphi = 45°$), local pure Mode II loading conditions exist.

Table 2

	$x_1 \equiv x_0$	$x_2 \equiv y_0$	$x_3 \equiv z_0$
$x'_1 \equiv x_m$	1	0	0
$x'_2 \equiv y_m$	0	Cos φ	Cos (90-φ)
$x'_3 \equiv z_m$	0	Cos (90+φ)	Cos φ

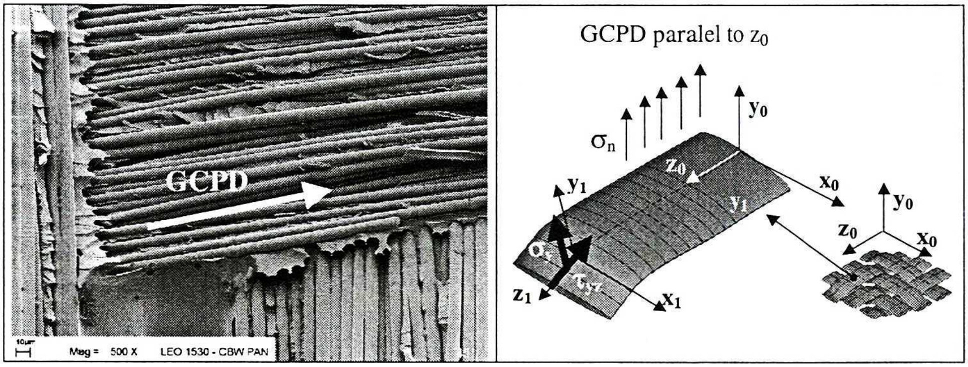


Fig. 10. Yarn parallel to the GCPD. Fracture created under global Mode I loading conditions. For the certain fracture regions the features characteristic for Mode II and Mixed Mode I/II are clearly visible

A similar analysis can be carried out for the global Mode II loading for the yarns parallel to the GCPD. As in the previous case, due to the normal and shear stresses acting at x_1z_1 plane, Fig. 11 the fracture at location 1 revels features characteristic for the Mixed Mode I/II loading.

However, two differences should be mentioned, i.e. for $a_{11} = \frac{\sqrt{2}}{2}$, ($\varphi = 45°$), instead of the local pure Mode II the local pure Mode I loading conditions exist and the slopes of hackles are opposite to those in the case of global Mode I loading.

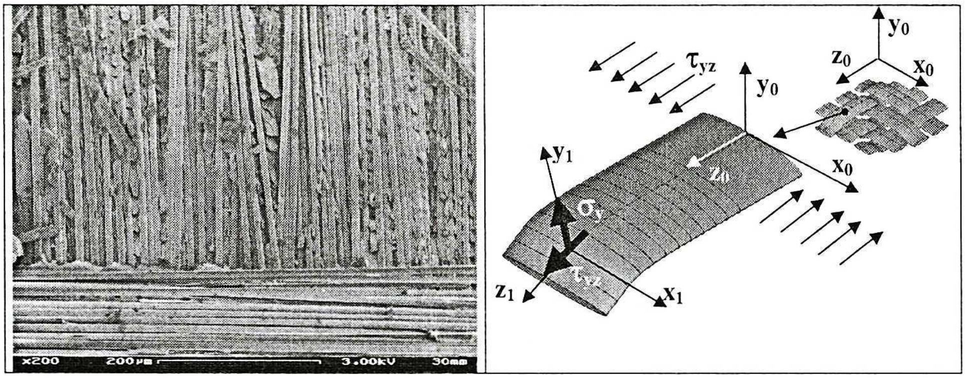


Fig. 11. Yarn parallel to the GCDP. Fracture created under global Mode II loading conditions. For the certain fracture regions the features characteristic for Mode II and Mixed Mode I/II are clearly visible.

For the yarns perpendicular to the GCPD, the fracture features visible in fracture area 2, Fig. 9, in the planes parallel to x_2z_2, (for co-ordinate system x_2 y_2 z_2 the values of a_{ij} are shown in Table 3), indicate local Mode I loading conditions while the global Mode II loading is applied.

Table 3

	$x_1 \equiv x_0$	$x_2 \equiv y_0$	$x_3 \equiv z_0$
$x'_1 \equiv x_2$	Cos (φ)	Cos (90 + φ)	0
$x'_2 \equiv y_2$	Cos (90-φ)	Cos φ	0
$x'_3 \equiv z_2$	0	0	1

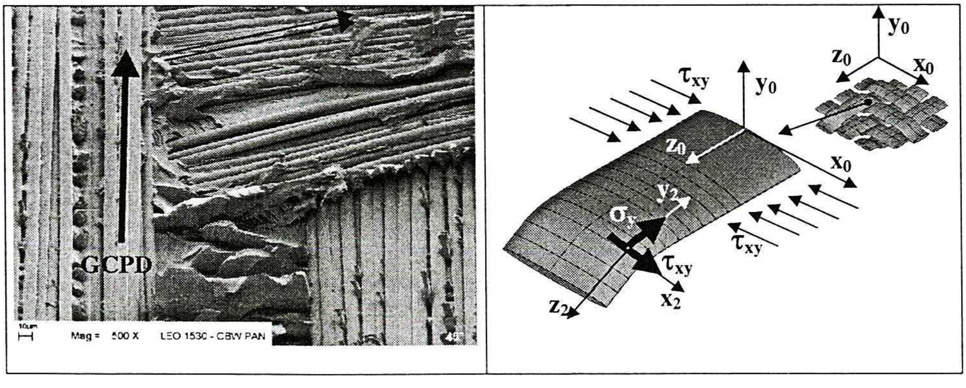


Fig. 12. Yarn transverse to the GCPD. Fracture created under global Mode II loading conditions. For the certain fracture regions the features characteristic for Mode II and Mixed Mode I/II are clearly visible.

As in the previous cases, after the fibre – matrix separation, the matrix fails in the cross sections bounded on both sides by the fibres and perpendicular to the principle tensile stress i.e. to which the normals make the angle of 45° to y_0 axis.

A similar consideration can be given for the reinforcement arrangement 45/45. The only difference is that for the global Mode II loading the corresponding global shear stress acting in the plane x_0y_0 should be resolved into components τ_{xy} and τ_{yz} determined in the local co- ordinate systems for the mutually perpendicular yarns, see Fig. 13. Further consideration is the same as in the cases shown in Figs. 11 and 12.

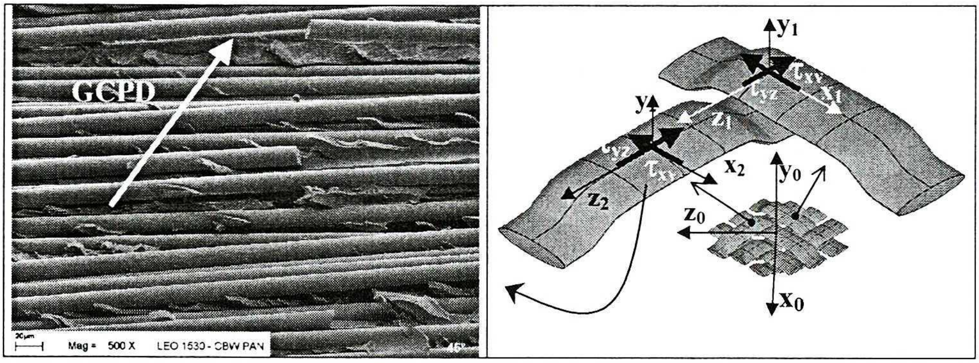


Fig. 13. Fracture surface forms resulting from Mode II loading for reinforcement arrangement 45/45

Other mechanisms contributing to the energy dissipation that increase critical the values of the strain energy release rate (SERR) consist in extensive fibre bridging indicated by a large number of fibres pulled out of the surrounding matrix as well as fibre breakage, Fig. 14.

Such an extensive fibre bridging is not visible in the case of UD reinforcement, and one could suggest that intensity of this phenomenon depends mainly on the yarn curvature due to weaving. Extensive fibre breakage occurs in the vicinity of the transverse yarns that act as a barrier for fibres pulling out and stop it enhancing the breakage process. Depending on the local lading, the fibres can fail in bending or tension, Fig.14 c and d, respectively.

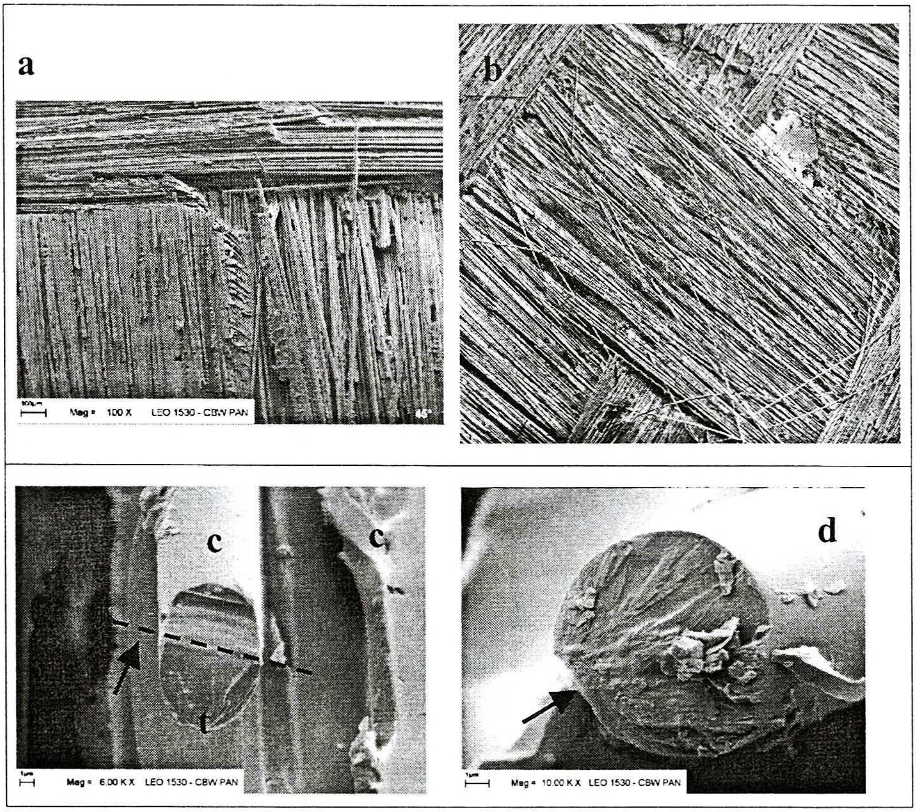


Fig. 14. Other mechanisms contributing to the energy dissipation: a) extensive fibre breakage enhancing by transverse yarns; b) pulled out fibres; c) and d) mechanisms of fibre failure, [6]: in bending and tension respectively. Dot line indicates neutral line and "c" and "t" indicate parts of fibre cross-section under compression and tension respectively (c); arrow indicates the origin of tensile failure (d)

4. Conclusions

The above considerations can be summarised as follows. There are several mechanisms responsible for a relatively high delamination resistance of laminates reinforced with fabrics. They result from yarn weaves and curvatures produced in the course of weaving. The yarn crossing do not allow for shifting the delamination to the location other than the initial one restricting the accompanying meso and micro cracking to the fabric layers adjacent to the general delamination propagation plane. It results in numerous intrayarn cracks and local crack bifurcations. Premature fibre – matrix separation results in overloading of the matrix cross sections between the fibres and causes their failures. Since the failures are due to the principal tensile stress, depending on location the fractures display features characteristic for Mode I or Mode II, or Mixed Mode I/II loading.

A number of mechanisms involved in the delamination process of laminates reinforced with fabrics are not understood. For example the mechanisms that are involved in delamination propagation in the regions of yarn surface parallel to the plane x_0z_0 under Mode II loading in the case of yarns transverse to the GCPD. Also, not clear are the reasons for which delamination resistance of laminates reinforced with fabrics of the orientation 45/45 is higher than that of 0/90. Therefore, further fractographic analysis is needed especially that *in situ* can be very helpful.

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Fraktograficzne badania odporności na rozwarstwienia kompozytów zbrojonych tkaninami

Streszczenie

W pracy przedstawiono wyniki badań fraktograficznych procesu rozwarstwiania zachodzącego w laminatach szklano-epoksydowych, zbrojonych symetrycznymi tkaninami szklanymi. Badania przeprowadzono w celu stwierdzenia przyczyn stosunkowo wysokiej odporności na rozwarstwienia laminatów zawierających tego rodzaju zbrojenie w porównaniu z laminatami o zbrojeniu jednokierunkowym (UD). Wyróżniono kilka swoistych mechanizmów rozpraszania energii nie występujących w laminatach UD. Wydaje się, iż szczególnie istotną rolę odgrywają tu mechanizmy działające na poziomie wiązek włókien a wynikające z ich przeplotów oraz krzywizn wywołanych procesem tkania. Są to rozgałęzienia pęknięć wewnątrz wiązek i między wiązkami oraz lokalne rozwinięcia powierzchni pęknięcia spoiwa spowodowane lokalną obecnością warunków obciążenia odpowiadających II Sposobowi Pękania i mieszanemu I i II Sposobowi Pękania indukowanymi

przez zakrzywienia wiązek zbrojenia a pojawiających się w globalnych warunkach I Sposobu Pękania. Przedstawione przyczyny wysokiej odporności na rozwarstwienia laminatów zbrojonych tkaninami symetrycznymi oraz związane z nimi mechanizmy przypuszczalnie nie są kompletne co uzasadnia kontynuację badań, przy czym szczególnie obiecującymi wydają się badania *in situ*, których przeprowadzenie, dotychczas, nie było możliwe z powodu braku mikroskopu skaningowego, wyposażonego w urządzenie pozwalające na obciążenie próbki w komorze próżniowej.