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FRACTOGRAPHY OF INTERLAMINAR FRACTURE OF GF/EPOXY LAMINATES REINFORCED WITH FABRICS

Fractographic examination of laminates reinforced with 2x2 twill fabric were carried out. Two reinforcement configurations relative to the global direction of delamination growth (GDDG) were considered: warp/weft tows parallel to the GDDG and warp and weft tows aligned at 45° with it. It was found that unlike for UD reinforcement, pure global Mode I and Mode II loadings resulted in local fractures typical for mixed mode I/II loading for both the global loading modes and reinforcement orientations. The possible reasons for such fractures were provided with the help of simplified qualitative stress analysis.

Keywords: fractography, delamination, fabric reinforced laminates

ANALIZA PĘKNIĘĆ MIĘDZYWARSTWOWYCH W LAMINACIE SZKLANO-EPOKSYDOWYM WZMOCNIONYM TKANINAMI

Przedstawiono wyniki badań fraktograficznych pęknięć międzywarstwowych (delaminacji) laminatu szklano/epoksydowego, wzmocnionego tkaniną o splocie diagonalnym. Badane pęknięcia powstały w wyniku obciążania próbek belkowych w konfiguracji zdwojonej belki wysięgnikowej, powodującej I sposób pękania (ISP), oraz konfiguracji trzypunktowego zginania belki z rozdwojonym końcem, powodującej II sposób pękania (IISP). W celu jaśniejszego uzasadnienia interpretacji przedstawianych przełomów scharakteryzowano uprzednio przełomy laminatu zbrojonego jednokierunkowo, spowodowane wyłącznie I i II sposobem pękania. Istnieje szereg odnośnych publikacji i charakterystyczne cechy takich przełomów, pozwalające na pewną, jednoznaczną identyfikację sposobu pękania i związanego z nim mikromechanizmu, są dobrze udokumentowane. Wyniki badań pęknięć międzywarstwowych laminatów wzmocnionych tkaninami wykazały, że powierzchnia pęknięcia jest pofalowana, co jest wynikiem przeplotów wiązek włókien stanowiących watek i osnowę. Badania przeprowadzone za pomocą mikroskopu skaningowego wykazały, iż w przypadkach obu konfiguracji wzmocnienia i obu globalnych sposobów pękania, lokalnie, występowały przełomy, w których równolegle pojawiły się cechy charakterystyczne dla I i II sposobu pękania. Proporcje mikroprzełomów charakterystycznych dla obu sposobów pękania były różne dla różnych obszarów wiązek włókien i wiązało się to z różnicami w lokalnym ich nachyleniu w stosunku do środkowej płaszczyzny próbek, w otoczeniu której powinno istnieć jedynie naprężenie normalne lub styczne, zależnie od globalnego sposobu pękania. Na kilku przykładach zademonstrowano możliwości dedukcji lokalnego kierunku rozwoju peknięcia, wykorzystując charakterystyczne cechy pęknięć. Jakościowa analiza proporcji składowych tensora naprężenia, uwzględniająca lokalne, maksymalne zmiany nachylenia powierzchni pęknięcia, oszacowane na około 15°, dostarczyła przesłanek umożliwiających wyjaśnienie lokalnego, równoległego występowania cech I i II sposobu pękania. Stwierdzono, iż nawet niewielkie zmiany nachylenia powierzchni pęknięcia powodują pojawienie się znaczącej składowej normalnej i stycznej tensora naprężenia, co tłumaczy występowanie mieszanego sposobu pękania.

Słowa kluczowe: fraktografia, delaminacja, laminaty wzmocnione tkaninami

INTRODUCTION

Laminates reinforced with symmetric fabrics display better delamination resistance then that of UD reinforcement. There is experimental evidence for the fact that the delamination resistance of such laminates depends on the delamination growth direction relative to the reinforcement configuration, i.e. to the direction of fibre tows making up the warp and weft of the fabric.

By analysing the diagrams in Figure 1 it can easily be concluded that for symmetric fabrics, the possible range of delamination growth direction to consider is in the $\varphi = 0 \div 45°$ bracket, and that the G_{Ic} and G_{IIc} values corresponding to $\varphi = 0°$ and $\varphi = 45°$ could be the upper or lower band for delamination resistance of the laminate under consideration. Despite the better delamination resistance of such laminates comparing to that of UD reinforcement, there is a scant number of papers concerning the fracture mechanisms involved in the delamination process of laminates reinforced with symmetric fabrics and the reasons for their better delamination resistance. This paper focuses on this issue. It was investigated with the help of fractographic examination of glass/epoxy laminate delaminations that resulted from global pure Mode I and Mode II loadings of beam specimens loaded in Double Cantilever Beam (DCB) and End Notched Fracture (ENF) configurations, respectively. The fractographic findings were supported with some results of the simplified, qualitative state of stress analysis.

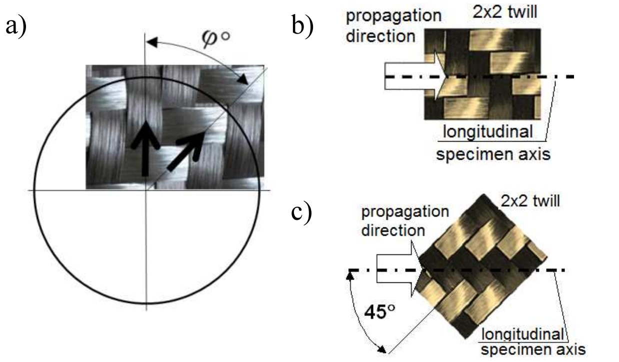

Fig. 1. Possible range of delamination growth directions for considered reinforcement configuration (a), 0/90 (b) and 45/45 configurations (c)

Rys. 1. Możliwy zakres kombinacji kierunków rozwoju delaminacji dla rozpatrywanych konfiguracji wzmocnienia (a), konfiguracja 0/90 (b) oraz 45/45 (c)

FRACTOGRAPHIC EXAMINATION

At first, reliable Mode I and Mode II fracture features are shortly presented, Figures 2 and 3, to facilitate successive fractographic analysis of laminates reinforced with fabrics. The shown features prevail solely over entire fractures in the case of UD reinforced laminates, however, as will be shown, it is not the case for laminates reinforced with fabrics.

Fractography of laminates with UD reinforcement. Reliable Mode I and Mode II fracture features

Mode I. In this case, bare fibres deprived of resin prevailed, Figure 2a. The fractured resin was solely visible just between the fibres. The resin surface appeared to be mostly flat and smooth, however, at high magnification textured microflow (feathering) was seen. Its presence is sound evidence of cleavage fracture indicating Mode I loading [1]. The local direction of crack growth can be deduced from the microflow lines since they converge towards the fracture origin [1, 2]. A relevant example of such a fracture is shown in Figure 2a. The resin fracture originated between the fibres and the crack propagated towards the nearest fibres. Often under Mode I loading, so-called river marks (lines) are formed. The directions in which they converge indicate the local direction of crack propagation [1, 2]. For example, in Figure 2b the crack propagated locally from the upper left-hand corner towards the lower right hand corner of the picture, i.e. the crack started at the fibre-resin interface and ran towards the neighbouring fibre while the global direction of delamination growth (GDDG) was from the top to the bottom of the picture.

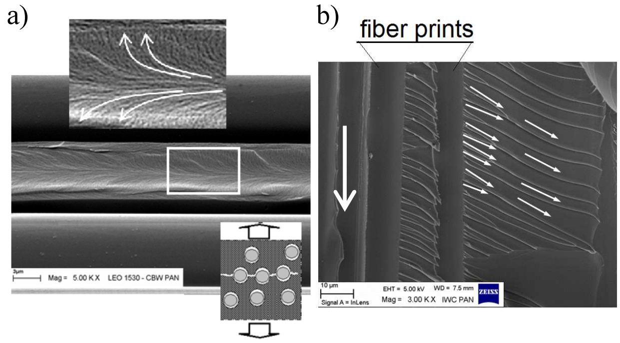

Fig. 2. Textured microflow feathering (a), river marks (b) indicate local direction of crack propagation

Rys. 2. Wzory piórowy (a) i dorzeczy (b) wskazujące lokalny kierunek rozwoju pęknięcia

Mode II. For Mode II loading, fibres were lacking in the matrix as well, however, the matrix fracture surface between the fibres was not flat as in the case of Mode I loading. At magnification of about 500x a saw-like pattern was clearly visible (Fig. 3a). This pattern was produced by closely spaced matrix cusps forming bands located between the pairs of parallel fibres.

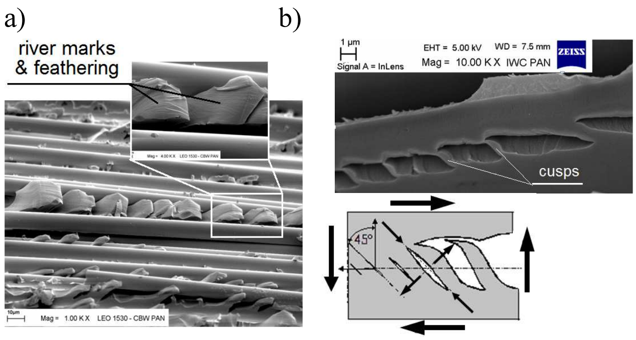

Fig. 3. Typical Mode II fracture (a) and cusp formation mechanism (b)

Rys. 3. Przełom II SP (a) i mechanizm powstawania zębów (b)

This pattern is recognised as a distinctive feature and sound indication of fracture due to Mode II loading [3]. The mechanism of cusp formation is sketched in Figure 3b. The formation of a cusp starts with several cleavage cracks produced by direct stress equivalent to shear stress resulting from global Mode II loading [1, 3]. Evidence of cleavage fracture can be seen under high magnification of about 10 000x. At this magnification the presence of textural microflow is clearly visible. It is claimed that by examining the river marks (if present) at several cusps, the global direction of crack propagation can be deduced [4]. Other fracture features that could be used to determine the GDDG are described in [5]. It is important to mention that the inclination of the cusps themselves does not constitute any evidence of crack growth direction [2].

Fractography of laminates reinforced with symmetric fabrics

The examined fractures were of glass/epoxy laminate reinforced with 2x2 twill fabric. For both the global fracture modes, two reinforcement arrangements, denoted 0/90 and 45/45, were considered (Fig. 1). Unlike in the case of UD reinforced laminates, laminates reinforced with fabrics contain interlaced filament tows of several thousands of filaments each. The tows cross each other at 90° (nominally). Such a fibre architecture results in tow undulation. Furthermore, the tows do not remain parallel to the global delamination plane but are of varying slopes that depend on location. The measurements indicated that for 2x2 twill, the slopes were shallow and the maximum inclination did not exceed 15° relative to the global delamination plane (middle plane of the specimen) (Fig. 4).

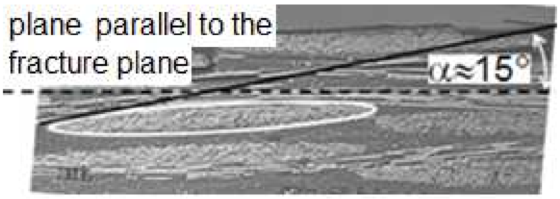

Fig. 4. Geometry of tow cross-section and tow centreline

Rys. 4. Geometria przekroju i szkieletowej wiązki włókien

a)

b)

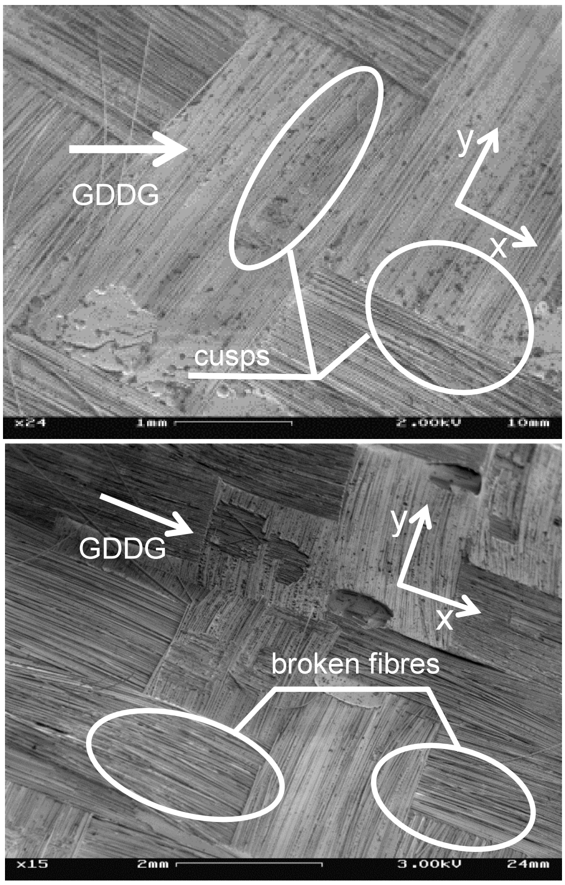

Fig. 5. Mode I fractures of 45/45 (a) and 0/90 (b) laminates. Arrows indicate global direction of delamination growth

Rys. 5. I SP; konfiguracje: 45/45 (a) i 0/90 (b). Strzałki pokazują globalny kierunek rozwoju delaminacji

Global Mode I fractures

The general appearance of the fractures due to global Mode I loading of 45/45 and 0/90 laminates is shown in Figure 5. Even under low magnification, it can be easily noticed that the appearance of the fractures varies from place to place and locally it closely resembles a typical Mode I fracture and at another location it closely resembles a typical Mode II fracture.

a)

b)

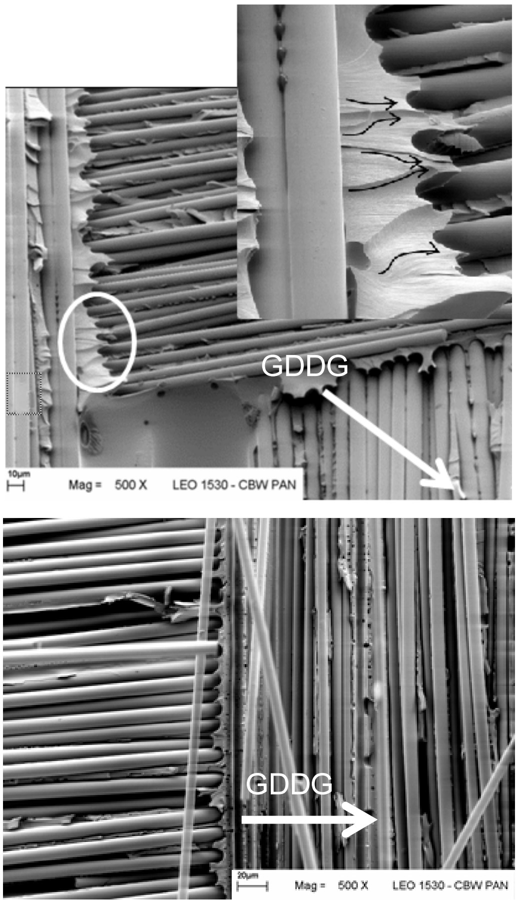

Fig. 6. Interlacing of warp and weft tows. Fracture due to Mode I loadings; 45/45 (a) and 0/90 (b) laminates

Rys. 6. Przeplot wątek-osnowa. I SP; konfiguracje 45/45 (a) i 0/90 (b)

This was found to be true of both 0/90 and 45/45 laminates. It can be seen that Mode I fractures of the 0/90 laminate displayed less resin damage but more fibre damage than the 45/45 laminate (Fig. 5). For the former, some resin cusps typical of a Mode II fracture were locally present, mainly at the tow slopes next to the warp-weft borders (Figs. 5a and 6a). Unlike for the 45/45 laminate, for the 0/90 laminate in the same regions resin cusps occurred very seldom, instead a number of fractured fibres was present (Figs. 5b and 6b). For both the reinforcement configurations, resin rich regions were present at the warp-weft boundaries. The details are shown in Figure 6. The resin formed ramps smoothing out tow undulations and in this way allowed the cracks to propagate from the warp to weft or from weft to warp tows. At the resin ramps, a microflow pattern occurred and allowed the crack propagation direction to be deducted. As an example, this feature is shown in Figure 6a for the 45/45 laminate, however, the same feature could be noticed in the case of the 0/90 laminate (not shown).

Global Mode II fractures

The general appearance of global Mode II fractures of 0/90 and 45/45 laminates is shown in Figure 7. As it was for pure global Mode I loading, even under low magnification, it can be easily noticed that for pure global Mode II loading, the appearance of the fractures varied from place to place and locally the fracture was of that closely resembling a typical Mode I fracture and at another location the fracture closely resembled a typical Mode II fracture. It was found to be true of both the 0/90 and 45/45 laminates. It could be seen that for the 0/90 laminate, the tow sections aligned with the GDDG at zero degrees displayed cusps i.e. a typical pure Mode II fracture feature.

a)

b)

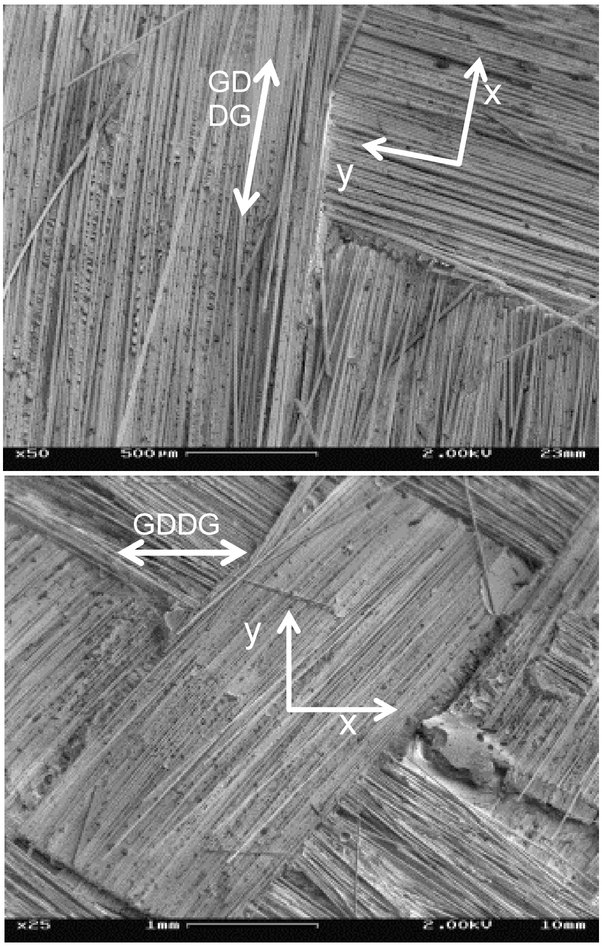

Fig. 7. Mode II fractures of 0/90 (a) and 45/45 (b) laminates

Rys. 7. II SP; konfiguracja 0/90 (a) i 45/45 (b)

The same was true for the 45/45 laminate. On the other hand, at the tow slopes a large number of broken fibres was present, while cusps were seldom. In these regions the fracture surface resembled that of typical Mode I loading. In the case of the 0/90 laminate, the tows perpendicular to the GDDG displayed typical Mode I features, while the tows parallel to the GDDG had an appearance typical of a Mode II fracture, however, this region was limited just to the flat tow sections. The inclined tow sections displayed fractures resembling that produced by Mode I loading. Some important fracture features were noticed in the proximity of the warp-weft resin rich borders. For the 0/90 laminate the tow perpendicular to the GDDG exhibited a typical Mode I fracture. At high magnification it was seen that in such regions the resin was peeled away from the fibres and hollows were formed (Fig. 8).

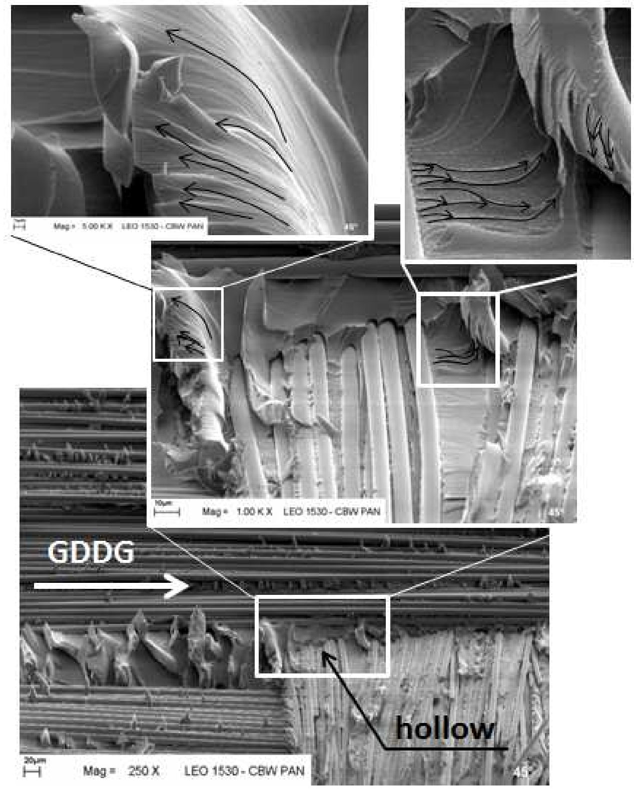

Fig. 8. Mode II fracture of 0/90 laminate. Small black arrows indicate local direction of crack growth deduced based on river marks

Fig. 8. Pęknięcie laminatu o konfiguracji 0/90, spowodowane II sposobem pękania. Czarne strzałki wskazują lokalny kierunek pękania, określony na podstawie wzoru dorzeczy

At the side walls of the hollow the resin displayed river marks, indicating that the crack propagated from the disclosed fibres (small black arrows). It should be mentioned that for the 45/45 laminate, it is rare that warp and weft tows are perfectly aligned at 45° with the GDDG. Usually some tows are at an angle less and some at angles larger than 45°. Larger numbers of cusps were visible between the fibres of the tows oriented at more acute angles than between the fibres of tows oriented at less acute angles. For the latter, the fractures were similar to that displayed by the transverse tows of the 0/90 laminate and a Mode I fracture was present locally as well. However, in this case fewer broken fibres were visible. Inspection of the resin fractures in these regions allowed the identification of river lines from which the GDDG could be deduced (Fig. 9).

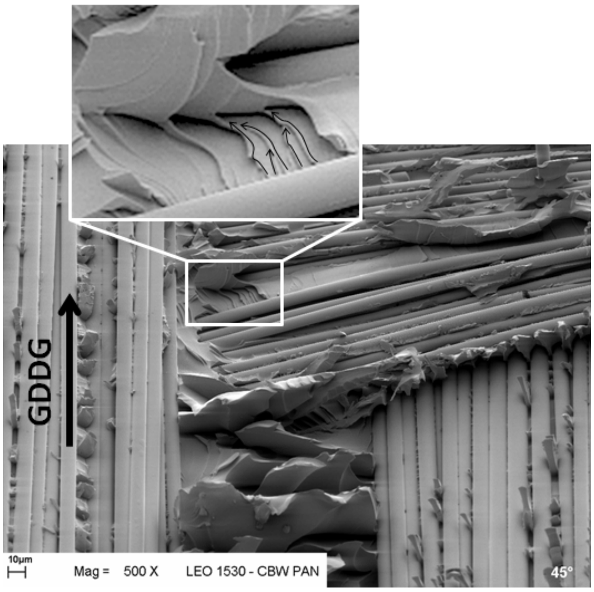

Fig. 9. Mode II fracture of 45/45 laminate. Small black arrows indicate local direction of crack growth deduced based on river marks

Rys. 9. Pęknięcie laminatu o konfiguracji 45/45, spowodowane II SP. Czarne strzałki wskazują lokalny kierunek pękania, określony na podstawie wzoru dorzeczy

QUALITATIVE STRESS STATE ANALYSIS

An explanation of the local occurrence of fractures not corresponding to the global loading modes could be given with the help of qualitative analysis of the local stress state in the proximity of the expected fracture surface. The aim of the presented analysis was to determine the proportions of stress components at the relevant fracture planes tangent to the assumed tow surface and resulting from pure Mode I and II global loadings. It was assumed that they could be represented by unit normal and shear stresses σ_{33}, and τ_{32} (for the 45/45 laminate) and $\tau_{3'1'}$ (for the 0/90 laminate), respectively. As shown in Figure 4, for the considered fabric the tow centre line was of moderate undulation and the tow cross-section could be approximated with an elongated ellipse. It was roughly estimated that the maximum slope of tow sides was about 15° relative to the global fracture plane. It was assumed that to a large extent the fracture surface enveloped the tows. This resulted in overall undulation of the fracture surface. From the point of view of the stress state analysis, several planes associated with such a tow geometry could be considered. Schematically, they are shown in Figure 10 and are tabulated in Table 1 together with the associated coordinate systems. Coordinate system 1”,2”,3” was defined by rotating coordinate system 1’,2’,3’ about axis 1’ by α = 15°, and coordinate system 1’’’,2’’’,3’’’ by rotating the 1’,2’,3’ system about axis 2’ by β = 15°, and coordinate system 1^{IV}, 2^{IV}, 3^{IV} by rotating the 1’’’,2’’’,3’’’ system about axis 1’’’ by γ = 15°. The numbers given in the rows of Table 1 represent fractions of unit normal or shear stress corresponding to the pure global loadings.

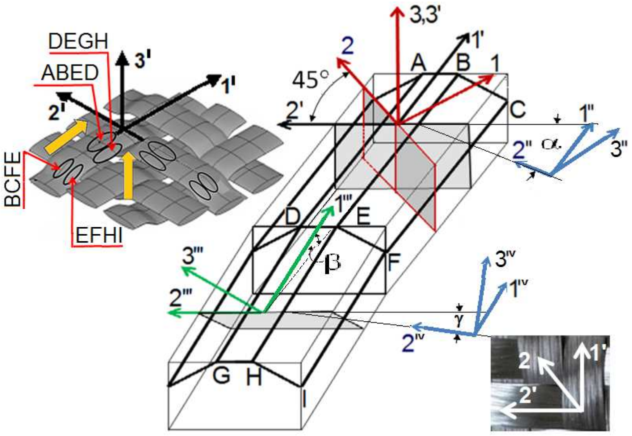

Fig. 10. Fracture planes under consideration and associated coordinate systems

Rys. 10. Analizowane płaszczyzny pęknięcia i odpowiadające im systemy współrzędnych

TABLE 1. **Considered fracture planes and associated coordinate systems**

TABELA 1. **Rozważane płaszczyzny pękania oraz związane z nimi układy współrzędnych**

	A B E D Coordinate system 1’, 2’, 3’ or 1, 2, 3					
Global	σ_1	σ_2	σ_3	τ_{23}	τ_{31}	τ_{12}
$\tau_{2'3'}$/ 90°	0	0	0	1	0	0
$\tau_{3'1'}$/ 0°	0	0	0	0	1	0
τ_{23}/ 45°	0	0	0	**1**	0	0
σ_3	0	0	**1**	**0**	0	0
	B C F E Coordinate system 1”, 2”, 3”					
	$\sigma_{1''}$	$\sigma_{2''}$	$\sigma_{3''}$	$\tau_{2''3''}$	$\tau_{3''1''}$	$\tau_{1''2''}$
$\tau_{2'3'}$/ 90°	0	.5	-.5	.87	0	0
$\tau_{3'1'}$/ 0°	0	0	0	0	.97	.26
τ_{23}/ 45°	0	.35	-.35	.61	.68	.18
σ_3	0	.07	.93	.25	0	0
	D E H G Coordinate system 1’’’,2’’’, 3’’’					
	$\sigma_{1'''}$	$\sigma_{2'''}$	$\sigma_{3'''}$	$\tau_{2'''3'''}$	$\tau_{3'''1'''}$	$\tau_{1'''2'''}$
$\tau_{2'3'}$/ 90°	.35	0	-.35	.68	.61	.18
$\tau_{3'1'}$/ 0°	.5	0	-.5	0	.87	0
τ_{23}/ 45°	.35	0	-.35	.68	.61	.18
σ_3	.07	0	.93	0	.25	0
Loc.	**E F I H** Coordinate system 1^{IV}, 2^{IV}, 3^{IV}					
Glob.	σ_{1iv}	σ_{2iv}	σ_{3iv}	τ_{2iv3iv}	τ_{3iv1iv}	τ_{1iv2iv}
τ_{23}/ 90°	0	.48	-.48	.84	-.07	.25
τ_{31}/ 0°	.5	-.03	-.47	-.16	.84	.22
τ_{23}/ 45°	.61	0	-.61	.61	.38	.35
σ_3	.07	.06	.87	.23	.24	.06

Depending on the already mentioned reinforcement arrangements, i.e. 45/45 or 0/90, the GDDG was in direction 2 or in 1’(2’), respectively as indicated by the pictogram in Figure 10. It is worth noting that for Mode

I loading, the stress components did not depend on the tow orientation which was not the case for Mode II loading.

CONCLUSIONS

Unlike in the case of the delamination of laminates with UD reinforcement, a great deal of evidence for the local occurrence of mixed mode I/II fractures in spite of pure Mode I or II global loading was found. In general, for both the 0/90 and for 45/45 laminates and pure loading modes, mixed mode I/II fractures were present with a varying mode ratio (Mode I)/(Mode II). This phenomenon could be attributed to the interlacing of the weft and warp tows and their undulations. Such undulations resulted in variation of the tow surface slope with location. Simplified qualitative analysis of the stress state at the singled out planes tangent to the tow surface showed that even small local deviation of the fracture plane from the global one (middle plane of the specimen) due to the aforementioned geometry of tows, resulted in the appearance of both normal and shear stress components in the same plane, explaining the presence of mixed-mode fracture.

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