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# The effect of edge interlaminar stresses on the strength of carbon/epoxy laminates of different stacking geometry

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*Abstract*: The effect of edge interlaminar stresses on strength of carbon/epoxy laminates of different stacking geometry: cross-ply, quasi-isotropic and angle-ply laminates with additional 0º and 90º ply was studied. Coupons with two widths of laminates with an inverse stacking sequence were tested in static tensile tests. The effect of edge interlaminar stresses on strength was studied, by comparing the values of the tensile strength of laminate coupons of the same width with an inverse stacking sequence, as well as, by comparing the values of the tensile strength of the same lay-up laminate coupons but of different widths. The edge effects were analysed by observing failure, identifying the interlayer where axial cracks at the free edge were initiated or inhibited and by computing interlaminar stresses and strains in the interlayer near the free edge of the coupon. The established edge effect was first correlated to the sign of the normal edge interlaminar stress. The extent of the edge effect was then successfully correlated to the edge interlaminar normal stress normalized to the size of the edge boundary region in which the stress appeared.

*Keywords*: fibre polymer composites, strength, edge interlaminar stresses, complementary energy.

## INTRODUCTION

In fibre-reinforced laminates subjected to an axial load, normal ($\sigma_z$) and shear interlaminar ($\tau_{xz}$) stresses (Fig. 1) arise at their free edges due to a mismatch in the elastic properties between the plies. Hence, in the region near both free edges of a coupon, known as the edge boundary region (EBR), highly localized interlaminar stresses make a fully three-dimensional stress field. This stress filed cannot be accurately predicted by classical lamination theory, only by a variety of suitable analytical and numerical methods.[1,2] The EBR width on one coupon free edge ($b_{EBR}$) is equal to the coupon depth,[2] $b_{EBR} = d$.

Edge-induced, interlaminar stresses can play an important role in the initiation of an axial crack in the interlayer and can lead to delamination and failure of the laminate at

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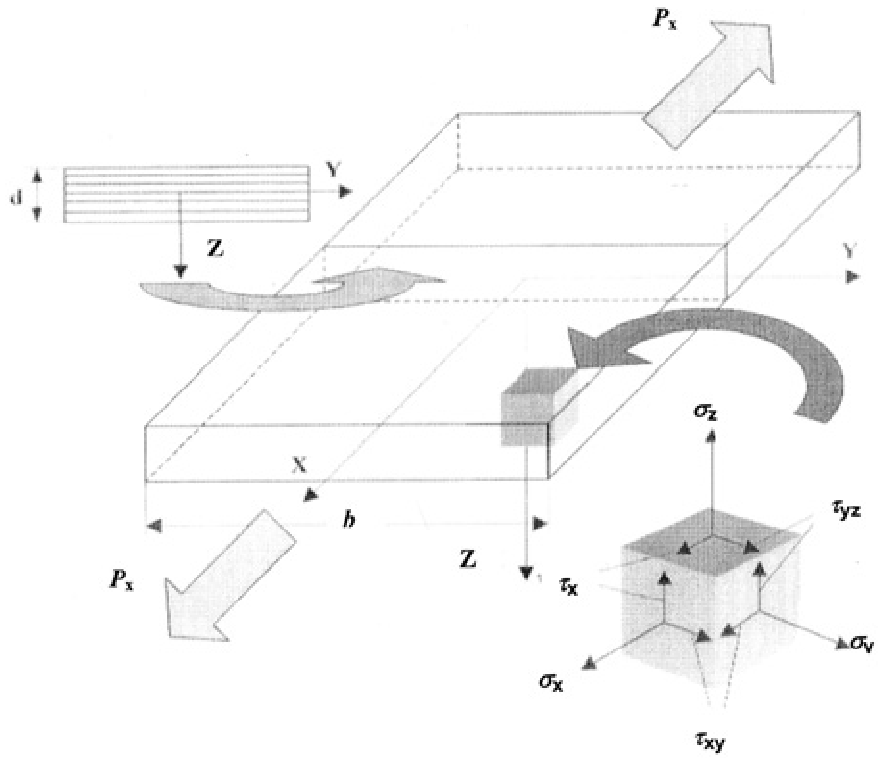


Fig. 1. Laminate coupon of depth *d* and width *b*, under load $P_x$, oriented in reference coordinate system X–Y–Z.

in-plane loads significantly lower than the loads at which the laminate would fail if only in-plane fracture was the failure mechanism. As a consequence, the measured effective strength has a lower value than expected. The edge effects are more or less pronounced depending on the stacking geometry of the laminate and can sometimes even supress the initiation of delamination and bring about a strength improvement.

Since the early seventies, numerous investigators have studied the effect of edge interlaminar stresses on the axial strength of fibre-reinforced laminates. Pipes and Pagano[3,4] and Rybicki and Schmueser[5] found that the sign of the transverse, normal edge interlaminar stress determines the edge effect on the tensile strength of cross-play laminates. They also showed that when the interlaminar stress, $\sigma_Z$, is of the tensile type, such as in laminates of $(0/90)_S$ stracking geometry, $\sigma_Z$, is instrumental in precipitating delamination in the 0º/90º interlayer. This leads to subsequent laminate strength degradation. The compressive edge induced normal interlaminar stress arising in the 90º/0º interlayer of $(90/0)_S$ coupons, inhibiting axial crack appearance, makes the tensile strengths of $(90/0)_S$ coupons higher than these of $(0/90)_S$ ones. Whitney and Browning[6] interpreted, in the same way, the results of the tensile strength of $(\pm45/90)_S$ and $(90/\pm 45)_S$ laminates. In later papers, attention was paid to a more accurate evaluation of edge interlaminar stresses and their distribution,[7,8] as well as, to the use of failure criteria, in connection with stress analysis in the assessment and explanation of the edge effect.[9]

In this paper, on the basis of the established edge effect and the presence or absence of interlaminar cracks in interlayers of failed coupons, the edge effect was first related with the sign of the normal interlaminar stress, as in the pioneering work of Pipes and Pagano[4] and in our previous paper.[10] Then, an effort was made to correlate the extent of the edge-effect with a parameter including both the numerical values of the interlaminar stress inducing or sustaining crack initiation, and the coupon thickness-to-width ratio ($d/b$). By applying such a parameter to the case where edge interlaminar shear stress $\tau_{xz}$ is responsible for crack initiation in a 45º/–45º interlayer, the edge effects in narrow coupons of $(0_2/\pm45)_s$ and $(90_2/\pm45)_s$ angle ply laminates were explained.

The coupons of cross-ply, quasi-isotropic and angle-ply laminates with 0º and 90º plies, all with an inverse stacking sequence, were tested on tension. To induce a more or less pronounced edge effect in the laminates, the tested coupons were of different widths.[11]

## EXPERIMENTAL

Laminates, obtained using a commercial, Hexcel M39 unidirectional carbon fibre/epoxy resin prepreg in the following stacking sequence* were studied:

cross-ply laminates: $(0/90)_s$ $(90/0)_s$

quasi-isotropic laminates: $(0/90/\pm 45)_s$ $(/\pm45/0/90)_s$

angle-ply laminates: $(\pm45/0_2)_s$ $(0_2/\pm45)_s$ $(\pm45/90_2)_s$ $(90_2/\pm45)_s$

The tensile tests of straight side tabbed coupons were performed on an M 1185 INSTRON Universal Testing Machine. The dimensions of the coupons with two different widths differed from that of standard coupons.

Transverse coupon failures, lateral sides of failed coupons with and without interlaminar cracks, and the main crack surface across the interlayer were observed at low magnifications on an optical microscope. Failure observation was made in order to establish whether and in which interlayer the axial crack appeared. The edge-induced interlaminar stresses calculated by the Kassapoglou and Lagace method,[12,13] based on the complementary energy** minimization principle. The interlaminar stress and strain components ($\sigma_z$, $\tau_{xz}$, $\varepsilon_z$ and $\gamma_{xz}$) for all interlayers present in the tested coupons were calculated along the coupon width, up to the free edge (shown in Fig. 2), and the values of the edge interlaminar stress ($\sigma_z$ and $\gamma_{xz}$) and strain component ($\varepsilon_z$ and $\gamma_{xz}$) at the free edges of the coupon were derived as a function of the $2z/d$ coordinate (shown in Fig. 3). The properties of a zero-degree orientation ply used in the calculations were:

* The ususal notation of the stacking sequence is used: the numbers refer to the ply orientation (angle between fibre direction and coupon length edge, *i.e.*, between the fibres and the direction of load application) and the subscript s denotes that the stacking sequence was repeated symmetrically about the centreline of the laminate.

** The definition of the laminate complementary energy, $\Pi_c$,[11] is the sum of the contribution of each of the individual plies ($\Pi = \sum_{k=1}^{n} \Pi_c^{(k)}$) $\Pi_c^{(k)}$, the complementary energy of the $k$-ply represents the difference between the total ply strain energy and the total ply strain work in the load direction, both per unit volume $\Pi_c^{(k)} = \Sigma U\varepsilon_{ij} - \Sigma W_x$.

$E_1 = 168.6$ GPa $E_2 = 9.52$ GPa $G_{12} = 3.72$ GPa $\upsilon_{12} = 0.298$

## RESULTS AND DISCUSSION

The edge effects were assessed by comparing the strength values of coupons of different widths of laminates with the same lay-up, as well as by comparing the strength values of coupons of a given width cut from laminate with an inverse stacking sequence.

For the purpose of correlation, the edge normal interlaminar stress $\sigma_{\text{z,edge}}$ "normalized" to the size of the edge boundary region for all the intelrayers present was calculated using the expression:

$$\sigma_{z,\text{EBR}} = \sigma_{z,\text{edge}} 2d/b \text{ [MPa]} \tag{1}$$

while for the 45º/–45º interlayer, the edge interlaminar shear stress $\tau_{xz,\text{edge}}$ "normalized" to the size of the edge boundary region was computed using the expression:

$$\tau_{xz,\text{EBR}} = \tau_{xz,\text{edge}} 2d/b \text{ [MPa]} \tag{2}$$

where $2d/b$ represents the edge boundary region part of the coupon, $d$ is the coupon depth, and $b$ is the coupon width. The computed values of $\sigma_{z,\text{EBR}}$ and $\tau_{xz,\text{EBR}}$ parameters, as well as, those of $\sigma_{z,\text{edge}}$ and $\tau_{xz,\text{edge}}$, are listed in Tables I – IV.

### *Edge effect in cross-ply laminates*

On the basis of the results presented in Table I, it can be stated that the effect of the edge in $(90/0)_s$ laminates on their strength is positive and in $(0/90)_s$ laminates negative, as has been known for years.[4] The microscopic and macroscopic evidence of failure confirms these conclusions. In the $(0/90)_s$-failed coupons, an axial crack appeared in the 0º/90º interlayer, while transverse fracture in $(90/0)_s$ coupons was neither initiated nor accompanied by any axial crack through the 90º/0º interlayer.

TABLE I. Tensile strength and edge interlaminar stress and strain of cross-ply laminates with a $(0/90)_s$ and a $(90/0)_s$ stacking sequence

| Stacking sequence | Coupon width/mm | Interply | $\sigma_z^{\text{edge}}$/MPa | $\varepsilon_z^{\text{edge}} \times 10^3$ | $\sigma_z^{\text{EBR}}$/MPa | $\sigma_z^{\text{exp}}$/MPa |
|---|---|---|---|---|---|---|
| $(0/90)_s$ | 15 | 0/90 | 16.0 | 2.63 | 4.05 | 766±34 |
| | 6 | 0/90 | 14.6 | 2.43 | 9.30 | 722±39 |
| $(90/0)_s$ | 15 | 90/0 | –17.8 | –1.83 | –4.51 | 815±46 |
| | 6 | 90/0 | –19.7 | –3.97 | –12.48 | 877±36 |

(Coupon depth $d$ = 1.9 mm)

For $(0/90)_s$ laminates, where a negative edge effect on the laminate strength was established, the edge interlaminar normal strength $\sigma_z$ and strain $\varepsilon_z$ are of the tensile type, while the positive edge effect in $(90/0)_s$ laminates is due to compressive interlaminar normal stress and strain (Table I).

The results confirm the known fact that the edge induced, normal interlaminar tensile stress (Tables I and II), is responsible for the detected negative edge effect on the tensile strength of $(0/90)_s$ laminate, as well as for axial crack initiation and propagation through the 0º/90º interlayer. However, a study,[14] based on the mechanics of linear fracture of delamination growth between orthotropic layers in a symmetric cross-ply laminate under in-plane normal tensile stress showed a negligible contribution of the Mode I (due to tensile stress) mechanism to delamination propagation compared with the Mode II (due to shear stress) and Mode III (antiplan or tearing Mode) mechanisms. This controversy can be understood taking into account the warping along the interlayer in the edge boundary region, pointed out by Reddy and Robbins,[2] as well as the gradient of the interlaminar stress and strain in the edge boundary region, recognised by the shape of the $\sigma_z = f(2y/b)$ and $\varepsilon_z = f(2y/b)$, curves (Fig. 2).

TABLE II. Tensile strength and edge interlaminar stress and strain of quasi-isotropic laminates with a $(0/90\pm45)_s$ and a $(\pm45/0/90)_s$ stacking sequence

| Stacking sequence | Coupon width/mm | Interply | $\sigma_z^{edge}$/MPa | $\varepsilon_z^{edge} \times 10^3$ | $\sigma_z^{EBR}$/MPa | $\sigma_{xz}^{exp}$/MPa |
|---|---|---|---|---|---|---|
| $(0/90/\pm45)_s$ | 12.4 | 90/45 | –165.4 | –17.39 | –26.68 | 585±45 |
| | 6 | 90/45 | –155.3 | –16.34 | –51.77 | 599±10 |
| $(\pm45/0/90)_s$ | 12.4 | – 45/0 | 180.4 | 19.60 | 29.10 | 548±88 |
| | 6 | – 45/0 | 131.4 | 14.28 | 43.80 | 407±32 |

(Coupon depth $d$ = 1.0 mm)

In quasi-isotropic laminates having a $(\pm45/0/90)_s$ stacking sequence, the negative edge effect on the laminate strength was established and the edge interlaminar normal strength $\sigma_z$ and strain $\varepsilon_z$ are of the tensile type (Table II). For a $(0/90/\pm45)_s$ stracking sequence, a positive edge effect was detected, which can be attributed to the compressive interlaminar normal stress and strain values computed for this lay-up. In the failed coupons with the former stacking sequence, the interlaminar cracks were observed in the – 45º/0º interlayer, while failure in the coupons having a $(0/90/\pm 45)_s$ laminate stacking sequence occurred without any axial crack in the interlayers present.

The extent of the edge effect cannot be correlated with the $\sigma_{z,\mathrm{edge}}$ and $\varepsilon_{z,\mathrm{edge}}$ values (Tables I and II). However, as can be clearly seen, without exception (Tables I and II), higher absolute values of the $\sigma_{z,\mathrm{EBR}}$ parameter were calculated for the coupons with a more pronounced edge effect, and *vice versa*. This means that the parameter $\sigma_{z,\mathrm{EBR}}$ can be used as a relative measure of a positive or negative edge effect on the inhibition or initiation of an axial crack in the interlayer, *i.e.*, on the increase or decrease in the measured laminate strength. By definition – Eq. (1), the $\sigma_{z,\mathrm{EBR}}$ parameter includes both the value of the edge interlaminar stress and the size of the edge boundary region where this stress is induced.

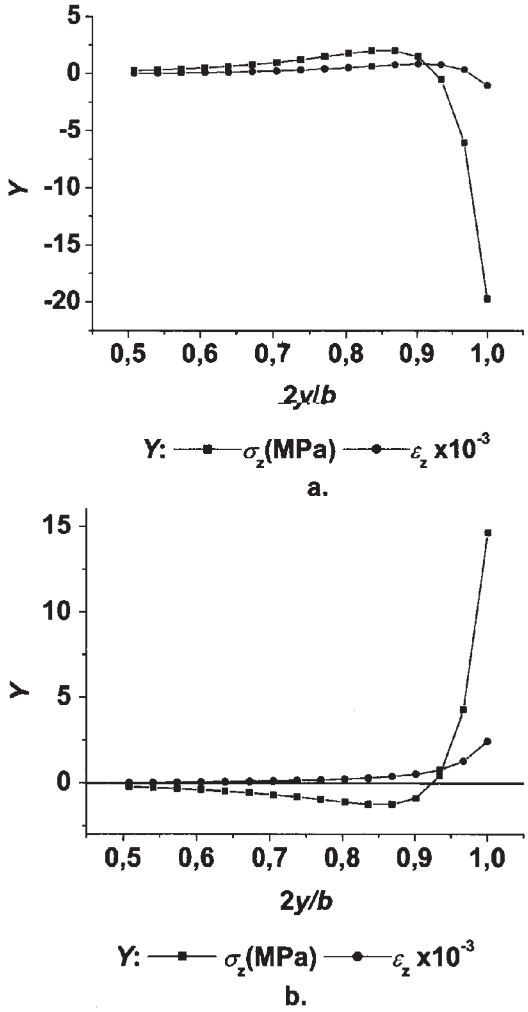


Fig. 2. Variation of the normal interlaminar stress ($\sigma_z$) and strain ($\varepsilon_z$) through the 0/90 degree interlayer along the coupon of width: a. $(90/0)_s$ laminate; b. $(0/90)_s$ laminate.

*Edge effect in angle-ply laminates*

The strength results obtained for narrow (6 mm) and wide (15 mm) coupons of angle-ply laminates with $(\pm 45/0_2)$ and $(\pm 45/90_2)_s$ stracking geometries (Table III), imply a negative edge effect in these laminates, because the strength values of the wider coupons were higher than those of the narrow ones. As in other similar cases,[4–6] the calculated edge interlaminar normal strength $\sigma_z$ and strain $\varepsilon_z$ are of the tensile type (Fig. 3). For laminates with these stacking sequences, the extent of the edge-effect is proportional to the value of the $\sigma_{z,\mathrm{EBR}}$ parameter (Table III). The parameter is a relative measure of the negative edge effect on the strength of laminates with $(\pm 45/0_2)_s$ and $(\pm 45/90_2)_s$ stacking sequences.

TABLE III. Tensile strength and edge interlaminar stress and strain of angle-ply laminates with a $(\pm45/0_2)_s$ and a $(\pm45/90_2)_s$ stacking sequence

| Stacking sequence | Coupon width/mm | Interply | $\sigma_z^{edge}$/MPa | $\varepsilon_z^{edge} \times 10^3$ | $\sigma_z^{EBR}$/MPa | $\sigma_x^{exp}$/MPa |
|---|---|---|---|---|---|---|
| $(\pm45/0_2)s$ | 15 | –45/0 | 50.9 | 4.18 | 6.79 | 902±52 |
| | 6 | –45/0 | 48.1 | 3.95 | 16.03 | 853±61 |
| $(\pm45/90_2)_s$ | 15 | –45/90 | 192.4 | 20.84 | 25.65 | 169±06 |
| | 6 | –45/90 | 143.9 | 15.58 | 47.97 | 129±02 |

(Coupon depth $d$ = 1.0 mm)

The strength values determined for 15 mm wide coupons of $(0_2/\pm45)_s$ and $(90_2/\pm45)_s$ laminates (Table IV) are higher than those determined for the same width coupons of $(\pm45/0_2)_s$ and $(\pm45/90_2)_s$ laminates (Table III) This can be explained by the fact that the interlaminar normal compressive stress in laminates where ±45º plies are near the mid-plane sustains the appearance of axial cracks in the 0º/45º and 90°/45° interlayers. On the contrary, the normal interlaminar tensile stress in laminates with outside ±45º plies induced visible axial cracks in the –45º/0º and – 45º/90º interlayers. Harris and Orringer,[15] as well as, Lee[16] reported edge delamination in the –Θº/90º interlayer of angle-ply laminates with an additional 90º ply.

TABLE IV. Tensile strength and edge interlaminar stress and strain of angle-ply laminates with a $(0_2/\pm45)_s$ and a $(90_2/\pm45)_s$ stacking sequence±×

| Stacking sequence | Coupon width/mm | Interply | $\sigma_z^{edge}$ MPa | $\varepsilon_z^{edge}$ $\times 10^3$ | $\sigma_z^{EBR}$ MPa | $\tau_{xz}^{edge}$ MPa | $\gamma_{xz}^{edge}$ $\times 10^3$ | $\tau_{sh}^{EBR}$ MPa | $\sigma_x^{exp}$ MPa |
|---|---|---|---|---|---|---|---|---|---|
| $(0_2/\pm45)_s$ | 15 | 0/45 | –59 | –9.34 | –7.87 | | | | 998±71 |
| | | 45/–45 | –103.2 | –13.38 | –13.76 | 27.6 | 17.86 | 3.68 | |
| | 6 | 0/45 | –51.5 | –8.15 | –17.17 | | | | 806±12 |
| | | 45/–45 | –90.1 | –11.7 | –30.03 | 24.1 | 15.75 | 8.03 | |
| $(90_2/\pm45)_s$ | 15 | 90/45 | –49.0 | –5.83 | –6.53 | | | | 210±4 |
| | | 45/–45 | –85.8 | –10.30 | –11.44 | 25.6 | 4.80 | 3.41 | |
| | 6 | 90/45 | –35.1 | –4.18 | –11.7 | | | | 143±12 |
| | | 45/–45 | –61.4 | –7.38 | –20.47 | 61.4 | 3.43 | 20.47 | |

(Coupon depth $d$ = 1.0 mm)

The values of the strength of wide and narrow coupons of $(\pm45/0_2)_s$ and $(\pm45/90_2)_s$ laminates (Table III), which reveal a negative edge effect on the laminate strength, can be fully explained by consideration of the earlier deseribed edge effect in cross-ply and quasi-isotropic laminates. The lower $\sigma_{z,\mathrm{EBR}}$ values of 15 mm coupons compared to those of 6 mm ones correspond to a less pronounced negative edge effect (higher strength values) in the wider coupons, while the higher $\sigma_{z,\mathrm{EBR}}$ values of the narrow coupons correspond to a more pronounced neg-

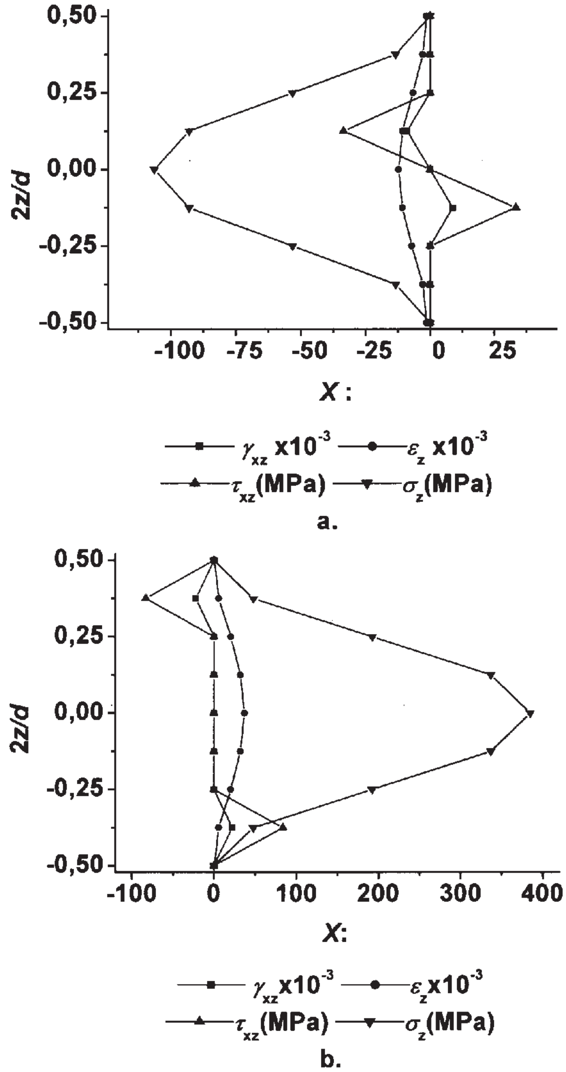


Fig. 3. Through-thickness edge interlaminar stresses ($\sigma_z$, $\tau_{xz}$) and strains ($\varepsilon_z$, $\gamma_{xz}$) as functions of the $2z/d$ coordinate for 15 mm wide coupons of:a. $(0_2/\pm 45)_s$ laminate; b. $(\pm 45/0_2)_s$ laminate.

ative edge effect (smaller strength values) in these coupons (Table III). This is because the cracks in these laminates appeared and were observed in the – 45º/0º and 45º/90º interlayers, due to the induced interlaminar normal tensile stress of edges.

However, it is not possible to explain the strength results of the narrower coupons of $(0_2/\pm 45)_s$ and $(90_2/\pm 45)_s$ laminates by such a consideration. Their strength was lower than that of the wider coupons (Table IV). The calculated $\sigma_z$ and $\varepsilon_z$ values in the interlayers of these coupons are of the compressive type. The wide coupons of $(0_2/\pm 45)_s$ and $(90_2/\pm 45)_s$ angle-ply laminates failed without noticeable axial cracks in any interlayer, under the recorded normal compressive edge interlaminar stress. However, in the narrow coupons of $(0_2/\pm 45)_s$ and $(90_2/\pm 45)_s$ laminates, short axial cracks, going from the transverse fracture border, were observed in the 45º/–45º interlayer. Undoubtedly, these cracks were initiated by induced edge interlaminar shear stress. Pipes, Kaminski and Pagano showed that "the crack initiated in 45º/–45º interlayer continues to grow through the matrix, propagates into the coupon and initiates premature ultimate rupture".[17] It makes the strength of these narrow coupons lower than that of wide ones. Emphasising that the damage growth in $(0/\pm\Theta_2)_s$ laminates is a complex process, Wharmby and Ellyin[18] also observed a continuous growth through the matrix of the crack initiated at the edge of the Θ/–Θ interlayer.

In narrow coupons of $(0_2/\pm45)_s$ and $(90_2/45)$, laminates, the $\tau_{sh,EBR}$ – Eq. (2) value for the 45º/–45º interlayer is higher than that for wide coupons (Table IV). This explains why the crack was initiated in the 45º/–45º interlayer of narrow coupons and not in the same interlayer of wide ones. This may be an argument to adopt the $\tau_{xz,EBR}$ (Eq. (2)) value as a measure of the edge effect when delamination occurs due to edge shear interlaminar stress.

## CONCLUSIONS

A positive edge effect, due to edge interlaminar normal compressive stress in the 0º/90º and 90°/45° interlayers, was observed in laminates of $(90/0)_s$ and $(0/90/\pm45)_s$ stacking sequences. In $(0/90)_s$ and $(\pm45/0/90)_s$ laminates, a negative edge effect was established due to edge interlaminar normal tensile stress in the 0º/90º and – 45°/0º interlayers. Laminate coupons, where a positive edge effect was established, failed without axial cracks through the interlayers, while in those where the edge effect was negative, premature final failure of the tested coupon was induced near free edges, by initiation and propagation of axial interlaminar cracks.

The parameter $\sigma_{z,EBR}$ was found to be a relative measure of the positive or the negative edge effect on the initiation or inhibition of a crack, *i.e.*, on the measured value of the laminate strength. It represents the edge interlaminar normal stress "normalized" to the edge boundary region (EBR) size. It includes the value of the normal edge interlaminar stress, as well as, the size of the EBR, where the edge interlaminar stress is induced.

In the tested coupons of angle-ply laminates of $(\pm45/0_2)_s$ and $(\pm45/90_2)_s$ stacking geometries, a negative edge effect was established, due to the induced edge interlaminar normal stress and strain of a tensile type. Axial cracks were observed in the – 45º/0º and – 45º/90º interlayers of the failed coupons of these laminates. The parameter $\sigma_{z,EBR}$ was approved as a relative measure of the negative edge effect for these laminate coupons.

A positive edge effect was observed in wide coupons of $(0_2/\pm45)_s$ and $(90_2/\pm45)_s$ laminates. The calculated edge interlaminar normal compressive stress sustained the appearance of axial cracks in the 0º/45º and 90º/45º interlayers of these coupons. In narrow coupons of $(0_2/\pm45)_s$ and $(90_2/\pm45)_s$ laminates, short interlaminar cracks going from a transverse fracture border were noticed in the 45º/–45º interlayer. They were initiated by induced edge interlaminar shear stress in this interlayer and grew continuously through the matrix. Propagating into the specimen, they inteated a premature ultimate rupture. In these laminates, the edge effect is negative and the parameter $\tau_{sh,EBR}$ – the edge shear interlaminar stress in the 45º/–45º interlayer, "normalised" to the relative size of the edge boundary region is a measure of its magnitude.

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ИЗВОД

## УТИЦАЈ ИВИЧНИХ ИНТЕРЛАМИНАРНИХ НАПРЕЗАЊА НА ЧВРСТОЋУ ЛАМИНАТА КАРБОН/ЕПОКСИД РАЗЛИЧИТЕ ГЕОМЕТРИЈЕ СЛАГАЊА

МОМЧИЛО СТЕВАНОВИЋ, МИЛАН ГОРДИЋ, ДАНИЈЕЛА ПЕШИКАН и ИСИДОР ЂОРЂЕВИЋ

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Проучаван је утицај интерламинарних напрезања на чврстоћу ламината карбон/епоксид различите геометрије слагања: попречно укрштених, квазиизотропних и угаоно укрштених ламината са слојевима оријентације 0º и 90º. Епрувете две ширине ламината са инверзним секвецама слагања ламина су испитиване у тестовима затезања. Утицај ивичних интерламинарних напрезања на чврстоћу је установљен поредећи вредности чврстоће епрувета исте ширине ламината инверзних секвенци слагања слојева, као и поредећи вредности затезне чврстоће епрувета различите ширине ламината исте секвенце слагања. Ивични ефекти су анализирани посматрањем разарања, идентификовањем међуслоја у којем су иницриране или инхибиране аксијалне пукотине, ако и прорачунавањем вредности ивичних интерламинарних напона и деформација. Установљен ивични ефекат је најпре корелисан са знаком нормалног интерламианрног напона. Степен ивичног ефекта је затим успешно корелисан са ивичним нормалним интерламинарним напоном нормализованим на величину граничне ивичне области у којој ниче интерламинарно напрезање.

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