FRACTURE MECHANICS FOR COMPOSITE BULK PROPERTY TESTING IN ORDER TO AVOID FRACTURE

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Abstract

Two existing composite shear tests which geometrically confine the test region with notches were modified using a fracture mechanics approach: the notches were viewed as mathematically sharp and analyzed using fracture mechanics. As successful modification was considered a cancellation of the principal stress- (or notch-) intensity factor. This was accomplished by either superimposing an additional load-set on an existing specimen set-up and geometry, or by modifying the specimen geometry for an existing set-up and loading. In both cases, substantial improvements were achieved with respect to stress uniformity. Specifically, the purpose of the modifications was to encompass individual composite properties such as laminate thickness and material orthotropy. The viability of this successful approach is demonstrated both numerically and experimentally on a strongly anisotropic composite laminate; optically recorded strain fields were significantly more uniform, and attainable load levels increased notably with the suggested modifications.

Background and Introduction

General testing

Measuring bulk properties at high load levels requires that localization and premature fracture can be avoided as long as possible: ultimately however, this will be the cause of specimen failure. During testing, it is important to ensure constant and well controlled conditions in a test region. Achieving this is intricate even in homogenous isotropic materials. Regarding composite materials, many more properties and effects need to be considered and particularly testing shear properties is among the most difficult[1,2]: at a free boundary, shear stresses must vanish while it is desired that they attain a constant (and known average) value in the test region. The only way to resolve these obviously contradicting requirements is to use a test without boundaries such as torsion of a thin walled tubular specimen. In all other tests, a trade-off between conditions at free edges and overall stress uniformity needs to be made. Typically, carefully designed specimens and rounded edges/notches are used to achieve this.

Stress fields and isotropic specimen with sharp notches

At a sharp notch (or crack), stresses are singular (in general[3,4]) and then approach different limits depending on from which direction the singularity is approached. Ultimately it is desired to have vanishing stresses on the notch boundaries and constant, but non-singular, stresses in the test region including the notch tip region. The Iosipescu shear test (developed for isotropic materials[5]) employs this concept successfully: the mode II singularity vanishes for a notch opening wider than $\theta > 102.6°$ In practice, however, $\theta = 110°$ and rounded notch roots are recommended in experiments. Only in isotropic materials under plane (stress or strain) conditions and with prescribed (and auto-balancing) surface tractions is the resulting stress field independent of material properties[6]. This is one underlying reason for the wide applicability and successful use of (elastic) fracture mechanics: plane conditions perpendicular to the crack front, loads applied as far field stresses, and the same resulting singular fields which are well defined through two stress intensity factors K_I and K_{II}.

Stress fields in inhomogeneous, anisotropic and orthotropic materials

In inhomogeneous materials, resulting stress fields are more complex as are the singular fields arising at corners or cracks. Both their shapes and magnitudes depend on all the elastic parameters involved. However, under the same plane conditions as mentioned above, the dependence on elastic parameters is reduced[7,8] and e.g. for a plane two-phase material the stress fields and singularities are uniquely defined by the Dundurs' parameters α and β[9]. Generally for anisotropic materials, the stress field depends on all elastic properties (C_{ijkl}, with 21 independent components) but again, similar reductions can be derived for arbitrary (plane) anisotropic materials[10]. Fortunately, plane conditions prevail in most relevant situations, and many composites (e.g. laminates) are orthotropic in that plane and thus described by four elastic parameters. Under analogous conditions, two parameters then suffice to uniquely determine the arising stress field for a given geometry and loading[11] as e.g. will be the case in a standardized test.

Cancellation of singular fields in composite shear tests

The standard Iosipescu test for composite materials prescribes (*ad hoc*) a notch angle of $\theta =$ 90°[12], whereas the resulting stress field depends on both the specific material properties and its orientation vis-à-vis the specimen. Consequently, this geometry is optimal only for one class of material properties (not explicitly specified) while it may be much less suited for others. However, the method of cancelling singularities may still be applicable for orthotropic materials but then requires modifications particular to the material and its testing orientation.

In this study, two composite shear test methods which both geometrically confine the test region with notches are addressed: the Iosipescu test[12] and the Double Notch Compression (DNC-) test[13]. They both measure shear properties in composite laminates, but on different planes: in-plane and through-thickness, respectively. In the analysis here, the notches are idealized as sharp cracks or notch roots and optimal testing conditions are determined by means of cancelling the arising singular elastic fields. Two different methods are employed: In the DNC test, an additional load-set (with no net contribution to the nominal load) is superimposed on a specimen with a given geometry. In the Iosipescu, on the other hand, the specimen is subjected to a well defined load, but its geometry is modified based on material constitutive properties. In both cases, the suggested modifications depend on laminate properties such as elastic constants and thickness etc.

Modifying Established Test Methods / Theory

IDNS

The Inclined Double Notch Shear (IDNS-) test uses the same specimen as the DNC-test[14,2], but subjects it to a combination of load cases: nominal compression (*N*) and bending (*M*) through support loads *R* and *P*, see Fig. 1. Here, *N* creates a nominal shear stress $\bar{\tau} = N/A$ in the test region, whereas the bending (*M*) does not contribute to any net stress. By treating the notches as mathematically sharp cracks, the local stress field is characterized by the arising stress intensity factors $K_\mathrm{I}^N = \sigma^N \sqrt{\pi a} f^N < 0$ and $K_\mathrm{I}^M = \sigma^M \sqrt{\pi a} f^M > 0$ for the respective load case. The IDNS-concept is to combine these load cases such that the total stress intensity factor vanishes, i.e. $K_\mathrm{I}^{tot} = K_\mathrm{I}^N + K_\mathrm{I}^M = 0$. The geometric functions f^N and f^M in the literature normally refer to isotropic materials.

In anisotropic materials, the stress intensity factors are still magnitudes of the $1/\sqrt{2\pi r}$ stress-singularities, and under a homogeneous stress state in the absence of boundaries, even the magnitude of K_I remains unchanged[4]. Ahead of the crack tip however, the stress field strongly depends on material anisotropy.

One intrinsic merit of the IDNS-test for composites is that the effect of material orthotropy on the stress field is allowed to carry through twice to the same extent, but with opposite signs. Thus, the IDNS method is quite insensitive to the material tested. Material orthotropy, ($\lambda = E_3/E_1$, see Fig. 1) only affects the already mild influence of nearby boundaries on f^N and f^M. But even these effects can be included through a simple rescaling procedure (lengthwise, by a factor $\sqrt[4]{\lambda}$) discussed below (see also [11,14] and compare in Table 2).

The proper mutual proportion among load cases (rendering $K_I^{tot} = 0$) is, with the present experimental set up, controlled by inclination of the specimen relative to an external load F by an angle $\alpha^\lambda = \alpha^\lambda\left(L, b, L_{tot}, f^N, f^M, \lambda\right)$, c.f. Fig. 1.

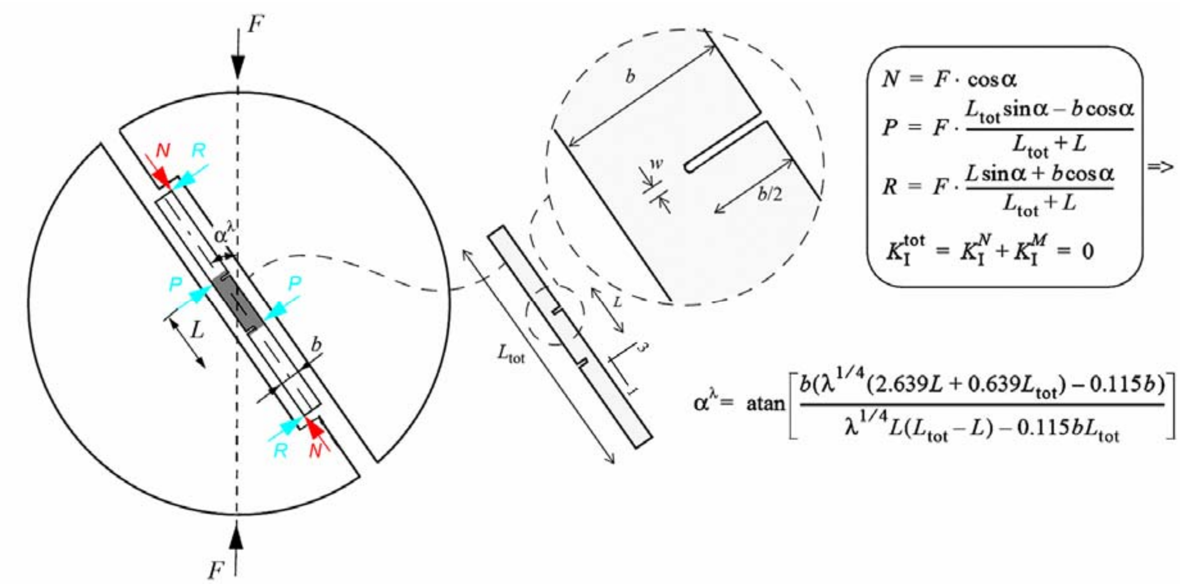

FIGURE 1. The IDNS test with inclined specimen, geometry and loads. Further, the fixture function, the external loading F, and the principal material directions are indicated.

Iosipescu

The specimen used in the Iosipescu shear test is subjected to asymmetric four point bending to obtain a state of pure shear in the test region, see also Fig. 2. To achieve a homogenous stress field for the composite materials, the specimen geometry is here modified with respect to the elastic properties.

As already mentioned, the resulting stress fields in plane orthotropic materials loaded with prescribed surface tractions are governed by only two parameters, here defined as:

$$\lambda = \frac{E_2}{E_1} \quad \text{and} \quad \rho = \frac{\sqrt{E_1 E_2}}{2G_{12}} - \sqrt{\nu_{12}\nu_{21}} \tag{1ab}$$

Analytical expressions for stress intensity factors for materials with cubic symmetry can under the same conditions be rewritten to be valid also for orthotropic materials through a simple rescaling procedure[11]. Stress fields in materials with cubic symmetry $(\lambda = 1)$ can under favorable conditions be well approximated by arising fields in isotropic ones, meaning that the dependence on ρ can be disregarded. This implies that the stress field in a plane orthotropic specimen with prescribed loading is equivalent with the stress state in (plane) cubic material with a rescaled specimen geometry. In the present situation, the geometry for the orthotropic specimen is chosen such that this rescaling procedure recreates the shape of the isotropic specimen, and consequently approximates the corresponding stress field in the original Iosipescu test (deemed to be the most favorable one[5]). Another interpretation of the above is that for most common plane orthotropic composite materials, the stress state is primarily dependent on the parameter λ, here called the orthotropy ratio (and to a lesser degree on ρ). The only practical effect of this lengthwise rescaling operation here is to modify the notch opening angle from originally $\theta_{\text{iso}} = 110°$, to a value θ depending on the orthotropy ratio:

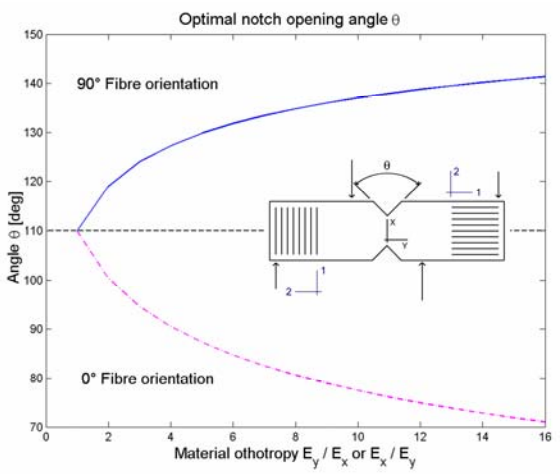

FIGURE 2. Optimal notch opening-angle according to equation (2) for varying orthotropy ratio. Fiber orientations are indicated.

$$\tan(\theta) = \frac{\tan(\theta_{\text{iso}})}{\sqrt[4]{\lambda}} \quad \text{where } \lambda = \frac{E_y}{E_x} \qquad \text{(2ab)}$$

Note that in equation (2) the directions and moduli in λ are defined with reference to the specimen directions shown in Fig. 2. This implies that for $\lambda < 1$, a sharper, and for $\lambda > 1$ a wider notch-opening angle than 110° is prescribed. Hence, the appropriate angle θ depends on along which principal orientation the material is tested, c.f. Fig. 2.

Numerical Analyses / Verifications

The analyses presented in the preceding section rely solely on straightforward mechanics and simple handbook formulae. To study the details, linearly elastic two-dimensional FE-analyses under the assumption of plane strain (IDNS) and plane stress (Iosipescu) are performed using the FE-code ANSYS. The material descriptions used in the analyses are all based on laminates built up by (pre-preg) lamellae of thickness 0.127 mm and with elastic properties according to Table 1.

TABLE 1. Elastic constants for the 0°-layers of the laminated orthotropic material

Young's Modulus	Shear Modulus	Poisson's Ratios
$E_1 = 160.0$ $E_2 = 10.0$ $E_3 = 9.4$	$G_{12} = 4.3$ $G_{23} = 3.2$ $G_{13} = 4.8$	$\nu_{12} = 0.310$, $\nu_{21} = 0.019$, $\nu_{23} = 0.518$, $\nu_{32} = 0.487$ $\nu_{31} = 0.018$, $\nu_{13} = 0.310$

IDNS

For the IDNS-test specifically, two different material descriptions for a 48 layer $[0^{o}/90^{o}]_s$-laminate are investigated: an individually layered and a homogeneously orthotropic model (with $\lambda = 0.149$ in the plane of loading) For comparison, also an isotropic material was included. Resulting shear stress distributions and specimen inclinations angles (α) (to cancel $K_{\text{I}}^{\text{tot}}$) are given in Fig. 3 and Table 2, for two different notch distances. For more details see [14].

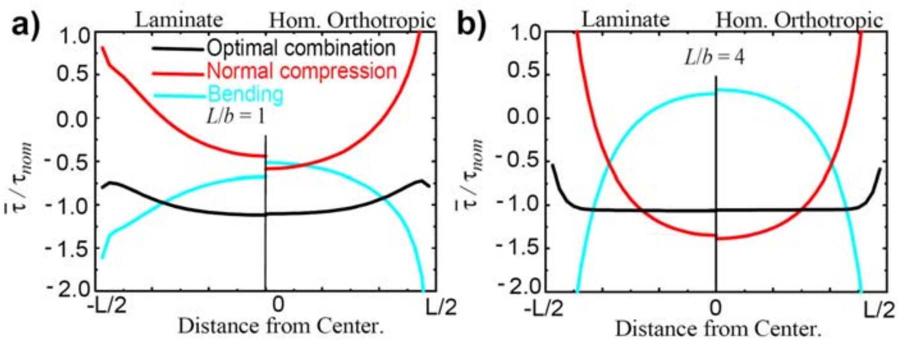

FIGURE 3. FE-calculated shear stress distributions in the test region for the load cases separately and their optimal combination. Two orthotropic materials are modeled: individually layered and homogeneously orthotropic for notch distances **a)** $L/b = 1$ **b)** $L/b = 4$.

TABLE 2. Proper specimen inclinations α from handbook formulae and FEM

L/b	α^{iso}	α^{λ}	$\alpha_{\text{FEM}}^{\text{Ortho}}$	$\alpha_{\text{FEM}}^{\text{Laminate}}$
1	46.1°	48.6°	48.5°	50.1°
4	28.3°	28.8°	28.8°	29.2°

Iosipescu

The effect of the orthotropic rescaling is verified numerically. The most homogenous stress distributions achieved without singularities are obtained for angles determined from eq. (2). Both sharper and wider notch angles θ than the optimal ones are studied, c. f. Fig. 4, and the mode II singularity, as expected, reappears for angles sharper than recommended by eq. (2)

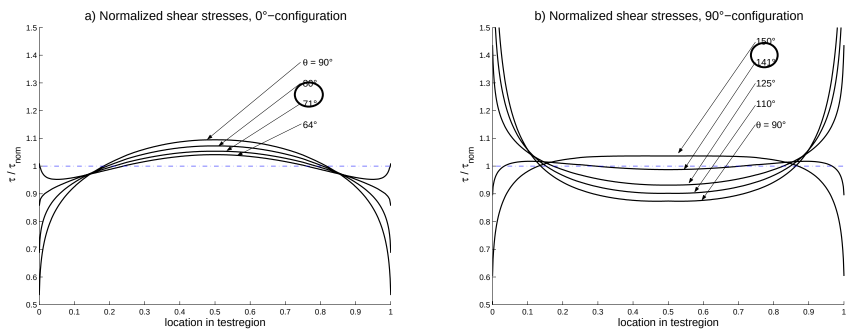

FIGURE 4. **a-b)** Normalized shear stress profiles for different notch opening angles, θ, with fibres aligned (0°) or crossing (90°) the test region. Optimal notch openings, according to eq. (2) are 71° and 141° respectively.

Experimental Verification

A panel consisting of 32 layers of a uniaxially oriented Fiberdux HTA/6376C carbon fiber/epoxy prepreg with a nominal panel thickness of 4.35 mm was used for the present investigation. Reported elastic properties are given in Table 1. For both test methods, specimens were manufactured using water jet cutting. Thereafter, specimens were finalized by diamond milling. Whole field strains were measured in the test region using Digital Speckle Photography (DSP) to study the shear strain uniformity in an experimental situation.

IDNS

Figures 5a-c show in-situ shear strain profiles for the IDNS-test and the DNC-test. With the specimen subjected solely to normal compression (i.e. DNC loading), shear strain concentrations appear in the vicinity of the notch roots, c.f. Fig. 5c, whereas these are effectively minimized with a superimposed bending load from forces *R* and *P*, c.f. Fig. 5a-b. With correct proportions among the load cases, a band of nearly constant magnitude of shear strain appears in the test region. However, shear strain concentrations are observed beneath the loading contact (due to forces *P*) at high loads near final specimen failure, see Fig. 5b. Table 3 show mean values of interlaminar shear strength (ILSS-) values obtained with the IDNS- and the DNC-test. Extensive experimental investigations of the IDNS-test and comparisons with other test methods can be found in [1,2].

TABLE 3. Exerimental ILSS-values

Method	$\bar{\tau}$ [MPa]
DNC $L/b=2$	58
IDNS $L/b=1$	132
IDNS $L/b=1.5$	114
IDNS $L/b=2$	111

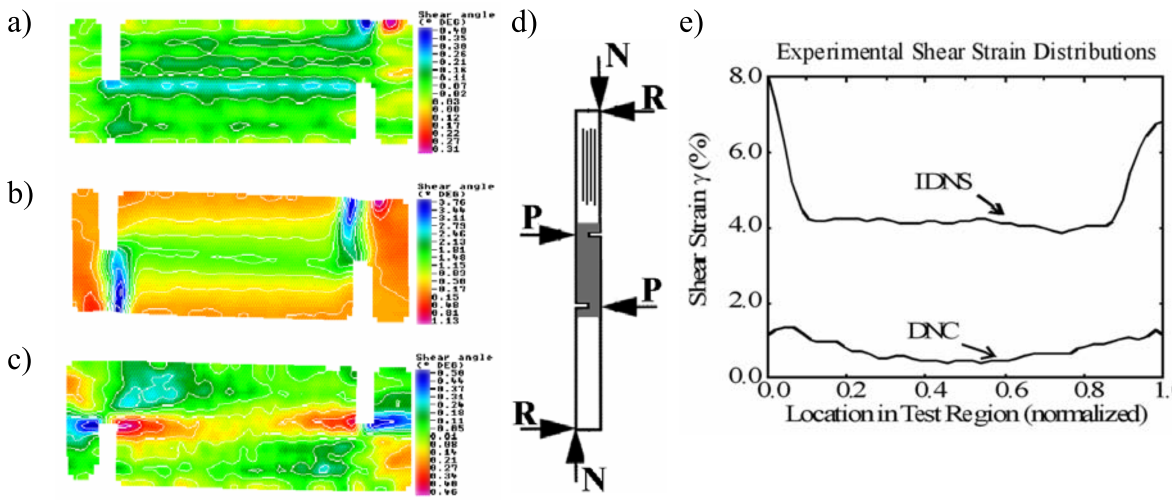

FIGURE 5. In-situ shear-strain fields at *L/b* = 2 in: **a)** IDNS-specimen at an intermediate load level (25% of peak load) and, **b)** an IDNS-specimen near final failure, **c)** DNC-specimen close to final failure, **d)** specimen with fibers and loading indicated and **e)** shear strain profiles for both test methods near to failure.

Iosipescu

The notch angles θ studied numerically (see above) were also tested experimentally. In Fig. 6, shear strain fields for standard and recommended geometries are shown, whereas test region profiles for all specimens can be seen in Fig. 7. Clearly, using the modified specimens,

a) $\theta = 90°$, $\tau_{nom} = 59$ b) $\theta = 71°$s, $\tau_{nom} = 56$ c) $\theta = 90°$, $\tau_{nom} = 97$ d) $\theta = 141°$, $\tau_{nom} = 68$

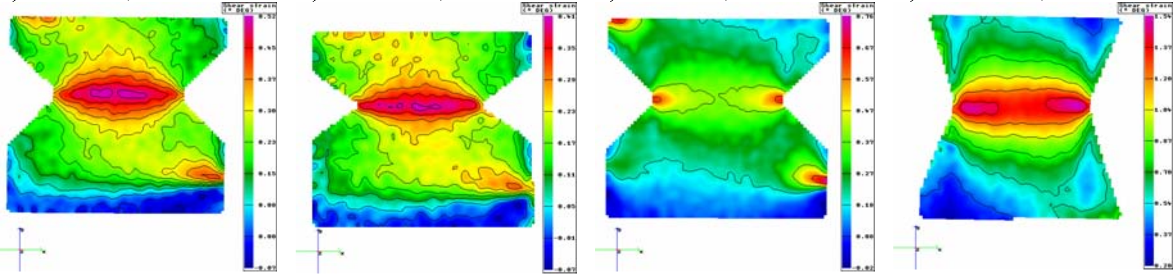

FIGURE 6. Shear strain profiles just prior failure. Shear stresses given in MPa and the non-uniform shear strain profiles levels are shown (in degrees, °) as $\varepsilon_{xy} = \gamma/2$. **a-b)** Fibres aligned with the test region (0°). **c-d)** Fibres crossing the test region (90°).

a more homogenous shear strain distribution is achieved and also higher strength levels are recorded, see Table 4. One specimen (with $\theta = 71°$) was manufactured with a sharp notch, instead of the normally rounded one, to investigate anisotropic Saint Venant´s effects. With fibres aligned with the test region, this effect is more important: then, notch root geometry affects strain profiles more than does notch flank angle θ [15]. To achieve known and uniform stress levels, giving a likewise uniform strain field, particularly important when measuring shear moduli with strain gages, see further in [5].

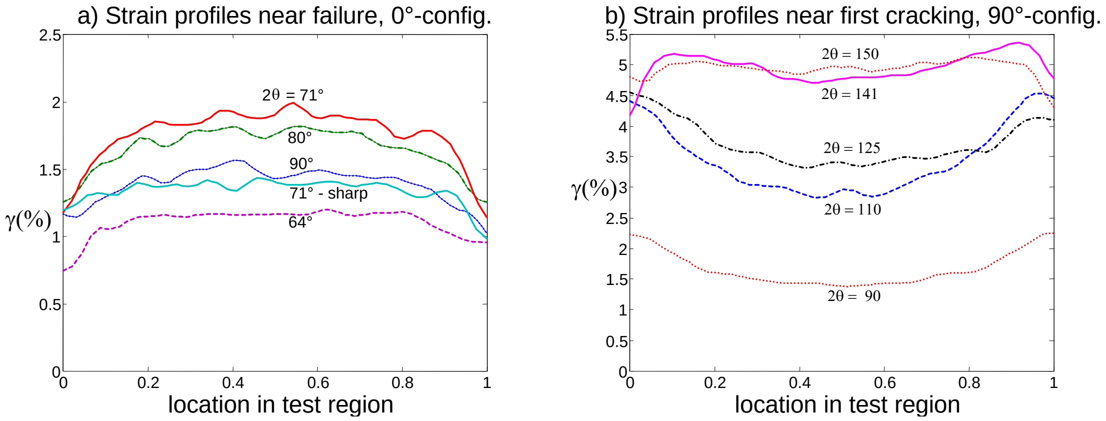

FIGURE 7. DSP measured shear strain profiles along the test region in all specimens at loads prior to failure/first cracking for **a)** fibers aligned with the test region, 0°-configuration, and **b)** fibers crossing the test region, 90°-configuration.

TABLE 4 Shear strength values ($\hat{\tau}_{12}$) for all tests (each from at least four specimens)

$\hat{\tau}_{12}$ [MPa] for	0^o-configuration					90^o-configuration				
angle 2θ=	64^o	**71^o**	$(71^o)^1$	80^o	90^o	90^o	110^o	125^o	**141^o**	150^o
first crack	57.8	**61.7**	$(50.3)^1$	56.8	60.7	76.6	91.4	94.8	**103.6**	94.6
ultimate	-	-	-	-	-	125.4^2	116.7^2	109.5^*	104.6^3	105.9^4

1) Sharpened notch
2) DSP strains are measured only on specimen front face
3) Strain gages are applied on both faces
4) Strains from test region center, not compensated for inhomogenous fields

Conclusions and Discussion

Although shear testing of composites still is elaborate and difficult, it is here shown that some of the inherent difficulties can be handled effectively with quite simple methods. These issues are the stress concentrations appearing particularly when testing through-thickness properties in thin panels (DNC-specimen), and the substantial influence of material anisotropy on resulting in-plane stress fields (Iosipescu test). In both cases, fracture mechanics considerations on idealized specimen geometries proved very successful for the experimental performance in practice. Notable is that the suggested modifications rely on material properties, i.e. E_1, and E_2 or E_3, but Young’s moduli are much easier to measure or to estimate from constituent properties than are shear properties. Composite testing requires both experience and careful handling, but the present modifications remove the principal causes for premature specimen fracture and thus facilitate determination of real and complete material bulk properties (i.e. at the highest loads) such as moduli, strengths and stress-strain curves.

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