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On the use of the combined FMC-ASED criterion for fracture prediction of notched specimens with nonlinear behavior

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Abstract

The Averaged Strain Energy Density (ASED) criterion has been widely used for the prediction of fracture conditions in a number of materials containing notch type defects, similarly to other well-known methodologies such as the Theory of Critical Distances (TCD). This criterion is linear-elastic, so the results obtained in linear-elastic materials have been accurate. However, as soon as the material behavior becomes nonlinear, the resulting accuracy decreases. With the aim of using linear-elastic simple methods (such as the ASED criterion) in nonlinear materials, several attempts have been made to convert a physically nonlinear behavior into an equivalent linear behavior. Thus, when the tensile behavior in plain specimens reveals nonlinearity, but the fracture behavior in the presence of defects is linear, the Equivalent Material Concept (EMC) has been successfully validated (EMC-ASED criterion). However, there are situations in which the nonlinear behavior takes place in both tensile and fracture behaviors, and the EMC-ASED criterion loses accuracy and requires further evolution. At this point, the Fictitious Material Concept allows the analysis of nonlinear materials (at both tensile and fracture conditions) to be performed with significant accuracy.
In this context, this article provides the prediction of fracture loads in single edge notched bending (SENB) specimens made of short glass fiber reinforced polyamide 6 (SGFR-PA6, 10 wt.%) containing U-notches and different levels of moisture content. The predictions are obtained through the combination of the FMC and the ASED criterion (FMC-ASED combined criterion). The results are significantly more accurate than those obtained through the ASED and the EMC-ASED criteria, but less accurate than those used when combining the FMC with the TCD.

Keywords: Fracture; FMC-ASED criterion, SGFR-PA6

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1. Introduction

Fibre-reinforced composites have become an important type of technical plastics, substituting other materials in engineering applications because of their easy fabrication and excellent mechanical performance (e.g., Banks (2006), Mallick (2007)). Among them, Polyamide 6 (PA6) is one of the most commonly used due to its combination of good processability, high mechanical properties, and chemical resistance (Brydson (1989)). Besides, when reinforcing PA6 with short glass fibers, there is a substantial increase in stiffness, strength, abrasion resistance and heat distortion temperature, without any penalty in the impact strength (Crawford (1998)). However, a significant issue of all polyamides (PAs) is their high moisture absorption capacity (Brydson (1989)), which can be a major disadvantage in applications where water is involved. Absorbed water in PAs leads to significant reductions in the elastic modulus, the yield stress and the glass transition temperature (Tg), although both the strain under maximum load and the fracture toughness may increase (Kohan (1995)).

When using short glass fiber reinforced polyamide 6 (SGFR-PA6) in structural components, this may be accompanied by the presence of notch-type defects that could, eventually, lead to fracture. Moreover, notched components develop an apparent fracture toughness (i.e., the fracture resistance in notched conditions) which is greater than the fracture toughness observed in cracked components, so assessing notches as if they were cracks is generally an over-conservative practice. Thus, specific approaches for the fracture analysis of notches have been performed using different failure criteria. Some examples are the Averaged Strain Energy Density (ASED) criterion (e.g., Sih (1974), Lazzarin and Berto (2005), Majidi et al. (2019)), the Theory of Critical Distances (TCD) (e.g., Taylor (2007)), Cohesive Zone models (e.g., Elices et al. (2001), Torabi et al. (2019)), and mechanistic models (Ritchie et al. (1973)), among others. The ASED criterion has been successfully applied to different materials and loading conditions. A complete description of this criterion, as well as an extensive application to different types of materials, was completed by Berto and Lazzarin (2014), and Lazzarin and Berto (2005) provided useful expressions that allow this criterion to be easily applied. The ASED criterion (and the TCD) has a linear-elastic nature and provides accurate predictions when analyzing fracture conditions in brittle materials. When applied in materials that are more ductile, the ASED criterion loses accuracy. With the aim of applying the ASED to nonlinear-elastic conditions, but keeping their simple linear-elastic formulation, it can be combined with the Equivalent Material Concept (EMC) (e.g., Torabi (2012)) or the Fictitious Material Concept (FMC) (Torabi and Kamyab (2019)). The former is applied in situations in which the tensile curve of the material is nonlinear, but the behavior of the notched components remain basically linear, whereas the latter is applied in those situations in which both the tensile and the fracture behavior are nonlinear.

With all of this, Section 2 provides an overview of the material being analyzed, the experimental program, and the FMC-ASED criterion, Section 3 presents the results and the corresponding discussion, and Section 4 gathers the final conclusions. The main aim is to validate the use of the combined FMC-ASED criterion for the fracture assessment of notched specimens with nonlinear behavior.

Nomenclature

a	defect size
A_{pl}	plastic area of the load-displacement curve of fracture specimens
e_{max}	engineering strain under maximum load
E	Elastic modulus
E^{FMC}	Elastic modulus of the fictitious material
J	J-integral
K	strain-hardening coefficient
K_c	fracture toughness expressed in stress intensity factor units
K_c^{FMC}	fracture toughness of the fictitious material, expressed in stress intensity factor units
K_I	stress intensity factor
Mc	moisture content
n	strain-hardening exponent

$P_{FMC-ASED}$	estimation of critical load using the FMC-ASED criterion
P_{max}	critical (experimental) load
$R_{c/FMC}$	control volume radius in the FMC-ASED criterion
W	specimen width
W_{avg}	average value of the SED
W_{cr}	critical value of W_{avg}
$W_{cr/FMC}$	critical value of W_{avg} in the FMC-ASED criterion
W_0	specimen weight in dry conditions
W_t	specimen weight after water absorption
ε_f*	strain at crack initiation for the virtual brittle material
ε_{max}	engineering strain under maximum load
ε_u	true plastic strain at maximum load
ρ	notch radius
σ_f*	tensile stress at crack initiation for the virtual brittle material
σ_u	engineering ultimate tensile strength
σ_y	yield strength
$\sigma_{0.2}$	0.2% proof strength
υ	Poisson´s ration
EMC	Equivalent Material Concept
FE	Finite Elements
FMC	Fictitious Material Concept
PA	Polyamide
ASED	Averaged Strain Energy Density
SENB	Single Edge Notched Bending (specimen)
SGFR-PA6	Short glass fibre reinforced polyamide 6
TCD	Theory of Critical Distances

2. Materials and methods

2.1. Material and specimens

The composite material studied here is short glass fiber reinforced polyamide 6 (SGFR-PA6, Durethan, Lanxess, Germany). The amount of fiber content is fixed at 10 wt.%, whereas the fracture specimens have five different notch radii (from 0 mm to 2.0 mm) and two different amounts of moisture (2% and 5%). The final 54 specimens were firstly fabricated with an injection-molding machine (Arburg Allrounder 221 K Arburg, Lossburg, Germany) in previously fabricated molds (see Figure 1a). The length of the short E-glass fibers s was 300 μm, the diameter being 10 μm, the ultimate tensile strength and the elastic modulus being 3450 MPa and 72.50 GPa, respectively, and the density being 2.60 g/cm3. 4 of the specimens were used for tensile testing (two per moisture content), and 50 of the specimens were used for fracture tests. The fracture specimens (SENB-type) were obtained from the central part of the tensile specimens (Figure 1b).

All the specimens were dried after the injection molding process in an oven at 100 °C. The initial weight in dry conditions (W_0) was measured before immersing the specimens in distilled water. Water uptake was controlled by weighing samples periodically until the desired weight was reached (W_t). The moisture content (M_c) follows:

$$\boldsymbol{M_c}(\%) = \frac{\boldsymbol{W_t - W_0}}{\boldsymbol{W_0}} * \mathbf{100} \quad (1)$$

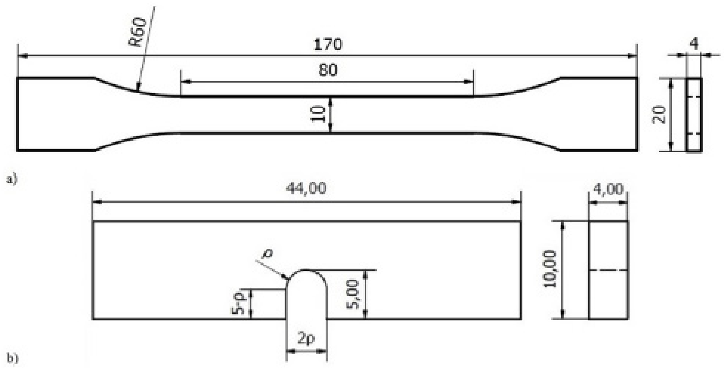

Fig. 1. (a) Tensile specimen (mm); (b) SENB specimens (mm) with notch radius (ρ) varying from 0 to 2 mm.

2.2. Tensile and fracture tests

Two tensile tests per moisture condition were performed following ASTM D638 (2010). The tests were all conducted at room temperature (20 °C) using an Instron 8501 universal test machine. The results (stress-strain curves, mean values and standard deviations) are shown in Section 3.

As mentioned above, 50 fracture SENB specimens were obtained from the central part of the remaining tensile specimens. The notches (performed perpendicularly to the longitudinal direction of the original specimens) were obtained by machining, except for the crack-like defects (those having a 0 mm notch radius), which were generated by sawing a razor blade. The former had a defect size (a) of 5.0 mm (a/W=0.5, W being the specimen width). Fracture tests were all conducted at room temperature (20 °C) using a Servosis ME-405/1 universal test machine and following ASTM D5045 (1999). The maximum loads reached in the different tests (P_{max}) and some of the load-displacement curves are gathered in Section 3.

2.3. The FMC-ASED criterion

According to the FMC, two important parameters, namely the fracture toughness and the tensile strength of the fictitious material, should be determined first. To do this by considering a simple calculation of the strain energy values required for crack growth to take place in both materials (i.e., the real nonlinear material and the fictitious brittle material), the load corresponding to crack growth onset in the fictitious material (see the parameter P_f* in Torabi and Kamyab, 2019) can be easily calculated. By applying this critical load to the finite element (FE) model of the pre-cracked specimen under pure mode I loading, the value of the fracture toughness of the fictitious material K_c^{FMC} can be determined, which is, in fact, the value of the stress intensity factor (SIF) associated with the critical load applied.

Based on the FMC, the values of the Young's modulus for the real ductile and fictitious brittle materials are different from each other. However, they have the same strains at the ultimate points. Figure 2 schematically illustrates the stress-strain curves for the real ductile and fictitious brittle materials. As depicted in Figure 2, both materials have the same strains at the ultimate points and different values of Young's modulus ($E \neq E^{FMC}$). In addition, the highlighted areas shown in Figure 2 identify the values of the SED for the two materials until the ultimate points. These areas are denoted herein by A_{Total}. By using the power-law model for the real ductile material, the value of SED until the ultimate point can be easily obtained from the following expression:

$$(\boldsymbol{SED})_{peak} = \frac{\boldsymbol{\sigma_y^2}}{\boldsymbol{2E}} + \frac{\boldsymbol{K}}{\boldsymbol{n+1}}[\boldsymbol{\varepsilon_u^{n+1}} - (\boldsymbol{0.002})^{\boldsymbol{n+1}}] \quad (2)$$

where σ_y, ε_u, E, K, and n denote the yield strength (e.g., 0.2% proof stress), the true plastic strain at the ultimate point, the Young's modulus, the strain-hardening coefficient, and the strain-hardening exponent, respectively. As is obvious in Figure 2b, the SED for the fictitious material until the final brittle fracture can be simply obtained by using the following equation:

$$(\boldsymbol{SED})_{FMC} = \frac{\boldsymbol{1}}{\boldsymbol{2}}\boldsymbol{\varepsilon_u}\,\boldsymbol{\sigma_f^{FMC}} \quad (3)$$

Therefore, assuming that the amounts derived from equations (2) and (3) are identical, the tensile strength of the fictitious material can be finally obtained as follows:

$$\boldsymbol{\sigma_f^{FMC}} = \frac{\boldsymbol{\sigma_y^2}}{\boldsymbol{\varepsilon_u E}} + \frac{\boldsymbol{2K}}{\boldsymbol{\varepsilon_u (n+1)}}[\boldsymbol{\varepsilon_u^{n+1}} - (\boldsymbol{0.002})^{\boldsymbol{n+1}}] \quad (4)$$

By substituting the values of the material parameters for SGFR-PA6 into Eq. (4), the tensile strength of the fictitious material $\boldsymbol{\sigma_f^{FMC}}$ can be obtained. The values of $\boldsymbol{K_c^{FMC}}$ and $\boldsymbol{\sigma_f^{FMC}}$ for the SGFR-PA6 materials associated with different testing conditions are presented in Section 3. More explanations about FMC can be found in the recent research paper published by Torabi and Kamyab (2019).

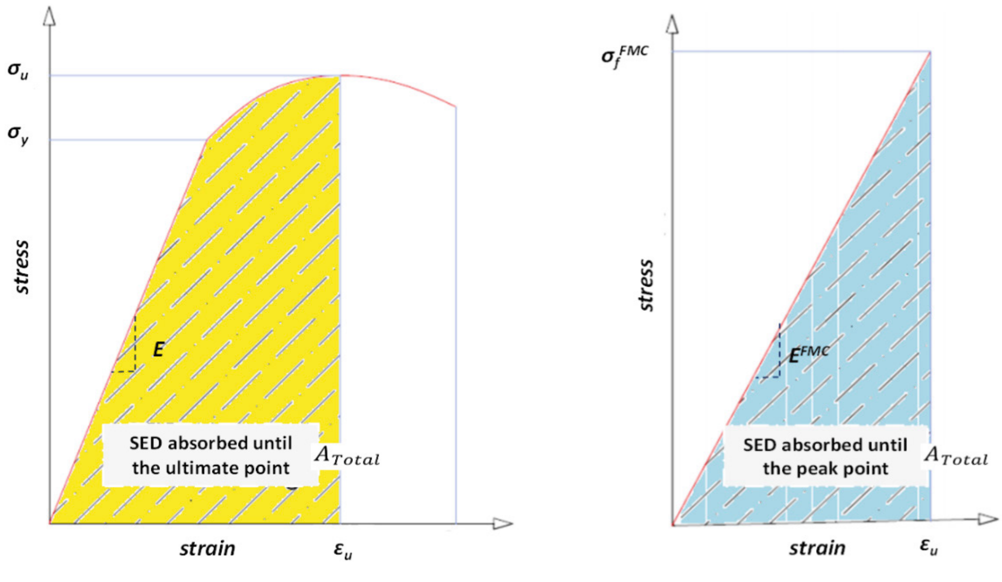

Fig. 2. Typical stress-strain curves for the real ductile (left) and fictitious brittle (right) materials.

According to ASED criterion, which is fundamentally a brittle fracture criterion in the context of linear elastic notch fracture mechanics (LENFM), when the average value of SED (W_{avg}) over a specified control volume surrounding the notch border reaches its critical value (W_{cr}), the notched specimen fails by brittle fracture. To estimate the failure loads of the notched components with nonlinear behavior by means of the linear elastic failure models, such as ASED, one can replace the fracture toughness and the ultimate tensile strength of the ductile material with the fracture toughness and the tensile strength of the fictitious material, respectively, and calculate the values of the control volume radius ($R_{c/FMC}$) and the critical SED ($W_{cr/FMC}$) by using Eqs. (5) and (6). The values of the control volume radius and the critical SED for the SGFR-PA6 materials with two different moisture contents are presented in Section 3.

$$\boldsymbol{R_{c/FMC}} = \frac{(\mathbf{5-3}\boldsymbol{\upsilon})}{\mathbf{4}\boldsymbol{\pi}}(\frac{\boldsymbol{K_c^{FMC}}}{\boldsymbol{\sigma_f^{FMC}}})^{\mathbf{2}} \tag{5}$$

$$\boldsymbol{W_{cr/FMC}} = \frac{(\boldsymbol{\sigma_f^{FMC}})^{\mathbf{2}}}{\mathbf{2}\boldsymbol{E^{FMC}}} \tag{6}$$

3. Results and discussion

3.1. Tensile tests

The main parameters obtained from the tensile tests are shown in Table 1 (Ibáñez-Gutiérrez et al. (2019)), whereas Figure 3 shows the corresponding strain-stress curves. One of the tests performed with 2% moisture content was not valid and it is not included in the results. It can be observed how the higher the moisture content the lower both the proof stress and the ultimate tensile strength, and the higher the strain under maximum load.

Table 1. Tensile parameters for the different levels of moisture content. E: elastic modulus; $\sigma_{0.2}$: proof stress; σ_u: engineering ultimate tensile strength; e_{max}: engineering strain under maximum load.

Moisture content	E (GPa)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	e_{max} (%)
2%	2.0	31.0	63.4	18.6
5%	0.95	22.5	47.7	22.7

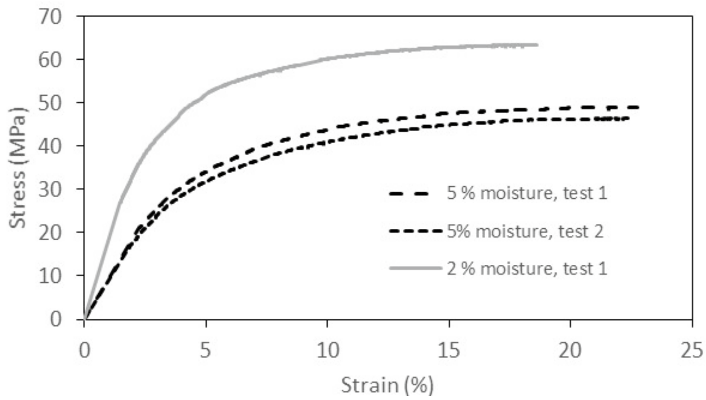

Fig. 3. Tensile curves obtained for the different levels of moisture content

3.2. Fracture tests

Figure 4 shows a couple of the load-displacement curves obtained in cracked specimens, which are also used to calibrate the FMC. The clear nonlinear behavior of the specimens containing 5% of moisture can be observed. This implies that the corresponding fracture toughness of the real material (K_c) obtained in the cracked specimens must be determined by using elastic-plastic formulation:

$$K_c = \sqrt{\frac{E \cdot J}{(1-\upsilon^2)}} \quad (7)$$

E being the elastic modulus, J being the J-integral at fracture, and υ the Poisson's ratio. J has two components, the elastic one (obtained through the applied stress intensity factor, K_I, at fracture), and the plastic one (obtained through the plastic area, A_{pl}, of the load-displacement curve).

Table 2 gathers the experimental fracture loads of the SENB specimens at both cracked and notched conditions, also showing the corresponding plastic area of the corresponding load-displacement curve. It can be observed how the fracture load is not very sensitive to the notch radius when the moisture content is 2%, whereas the fracture load moderately increases with the notch radius when the moisture content is 5%. However, the plastic area does increase with the notch radius for both moisture contents, the material becoming more nonlinear. Finally, the nonlinear behavior is much more significant for the specimen with 5% of moisture.

Table 3 summarizes the values of the control volume radius and the critical SED for the SGFR-PA6 materials with various moisture contents.

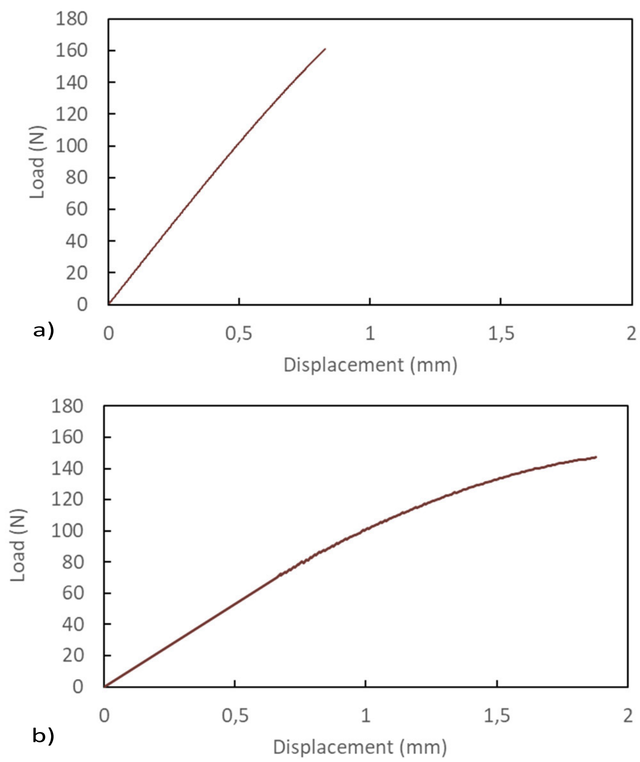

Fig. 4. Load-displacement curves obtained in two cracked specimens. (a) moisture 2%; (b) moisture 5%.

3.3. Fracture load predictions using FMC-ASED combined criterion

Table 4 lists the theoretically predicted and experimentally recorded fracture loads for the tested U-notched SGFR-PA6 specimens together with the discrepancies between the experimental and theoretical results. As seen in Table 4, the FMC-ASED model provides satisfactory predictions of the test results. In most cases, the accuracy of the predictions is good and in only two cases, the accuracy is low. By considering all the test data simultaneously, the average discrepancy for the FMC-ASED model is obtained to be equal to 12.7%, something reasonable in the fracture mechanics context, demonstrating the effectiveness of this model and suggesting that this model can be utilized as an efficient criterion for fracture prediction of notched components with nonlinear behavior.

Table 2. Experimental results for SGFR-PA6 (10 wt.%). M_c: moisture content; a: crack length; P_{max}: maximum load; A_{pl}: plastic area; ρ: notch radius; a=5 mm for non-crack defects (ρ=0.25 mm up to ρ=2.00 mm).

M_c (%)	ρ = 0 mm			ρ = 0.25 mm		ρ = 0.50 mm		ρ = 1.00 mm		ρ = 2.00 mm	
	a (mm)	P_{max} (N)	A_{pl} (N·mm)	P_{max} (N)	A_{pl} (N·mm)	P_{max} (N)	A_{pl} (N·mm)	P_{max} (N)	A_{pl} (N·mm)	P_{max} (N)	A_{pl} (N·mm)
2	4.55	157.9	5.76	150.9	11.70	145.30	11.76	136.3	11.70	145.4	17.05
	4.40	160.7	6.05	143.0	6.48	161.40	14.69	150.2	12.63	146.0	19.97
	4.37	173.8	7.84	146.9	12.82	140.01	16.78	154.7	17.62	133.1	10.17
	4.38	161.1	4.97	139.5	9.17	136.10	9.07	159.0	22.30	159.3	17.57
	4.25	188.1	9.49	145.7	7.40	132.30	8.85	143.9	12.94	160.4	33.60
5	4.54	147.1	63.54	138.1	69.13	137.00	82.63	152.9	207.87	168.0	377.90
	4.35	161.7	70.18	134.6	45.36	152.90	129.71	154.9	199.76	139.6	106.55
	4.59	153.8	53.91	141.8	71.13	131.20	73.47	152.3	179.00	152.7	160.38
	4.61	164.0	104.02	140.4	86.15	124.10	44.05	148.5	140.20	156.7	254.66
	non-valid			137.0	74.77	127.00	71.31	non-valid		165.0	282.34

Table 3. Properties of the fictitious material for different moisture contents.

Moisture content (%)	ε_u(%)	υ	A_{Total} (MPa)	E^{FMC} (MPa)	σ_f^{FMC} (MPa)	K_c^{FMC} (MPa·m$^{0.5}$)	$R_{c/FMC}$ (mm)	$W_{cr/FMC}$ (MPa)
2	18.62	0.38	9.91	571.64	106.44	3.87	0.406	9.91
5	22.72	0.38	8.79	340.45	77.35	4.32	0.958	8.79

Table 4. Estimations of fracture loads ($P_{FMC\text{-}ASED}$) obtained using FMC-ASED criterion

Moisture content (%)	ρ (mm)	$P_{Exp.ave}$ (N)	$ASED_{FMC}$ (MPa)	$P_{FMC\text{-}ASED}$ (N)	Discrepancies (%)
2	0.25	145.20	4.22E-04	153.29	5.6
	0.5	143.02	4.43E-04	149.63	4.6
	1	148.82	4.45E-04	149.30	0.3
	2	148.84	3.88E-04	159.83	7.4
5	0.25	138.38	2.68E-04	180.95	30.8
	0.5	134.44	2.73E-04	179.46	33.5
	1	152.15	2.91E-04	173.73	14.2
	2	156.40	3.21E-04	165.53	5.8
Average discrepancy					12.7

4. Conclusions

This paper presents the analysis of fracture processes in non-linear materials in both tensile and fracture conditions by using the Averaged Strain Energy Density (ASED) criterion, with linear-elastic nature. This requires the use of the Fictitious Material Concept (FMC), leading to the FMC-ASED combined criterion.

The resulting criterion has been applied to SGFR PA6 with 10% of fiber content (wt.%) and two different levels of moisture content (2% and 5%), as moisture increases significantly the non-linearity of SGFR PA6. The results obtained demonstrate that the FMC-ASED criterion is able to predict reasonable estimations of the experimental loads, constituting a useful tool in the fracture analysis of non-linear materials using linear-elastic (more simple) tools.

Acknowledgements

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