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Fracture loads prediction on notched short glass fibre reinforced polyamide 6 using the strain energy density

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This paper provides an energetic approach useful for the prediction of critical loads on U-notched components without an ideally linear elastic behaviour. The methodology has been applied to 100 fracture specimens of short glass fibre reinforced polyamide 6 (SGFR-PA6), combining four different fibre contents (5, 10, 30 and 50 wt %) and five different notch radii (0.00, 0.25, 0.50, 1.00 and 2.00 mm). The proposal combines the application of the strain energy density criterion with the use of the whole absorbed energy in the tensile test (elastic-plastic area under the stress-strain curve). With all of this, the fracture loads have been well estimated in this type of material.

Keywords: short glass fibre reinforced polyamide 6, strain energy density, notch, fracture assessment

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Расчет разрушающих нагрузок для образцов стеклонаполненного полиамида 6 с надрезом на основе критерия плотности энергии деформации

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В статье предложен энергетический подход для оценки критических нагрузок на элементы конструкций с U-образным надрезом для неидеального линейно-упругого поведения. Испытания на излом проводили на образцах стеклонаполненного (короткое волокно) полиамида 6 (SGFR-PA6) с разным содержанием волокон (5, 10, 30 и 50 мас. %) и разным радиусом надреза (0.00, 0.25, 0.50, 1.00 и 2.00 мм). Предложенный подход основан на применении критерия плотности энергии деформации с учетом всей поглощенной энергии в ходе испытаний на растяжение (упругопластическая область под кривой растяжения). Проведена оценка разрушающих нагрузок для данного типа материала.

Ключевые слова: стеклонаполненный полиамид 6, плотность энергии деформации, надрез, оценка разрушения

1. Introduction

The life of structural components is one of the main concerns that design engineers must address. When a stress riser is present (e.g., cracks or notches), it is very important to evaluate the load that leads to failure: the critical load or fracture load.

For many years, different criteria have been developed to assess both the ductile and the brittle behaviour of notched components. One of the first to be proposed, dating back to 1885, is the strain energy density (SED) criterion [1]. Since then, different SED-based approaches have been formulated (e.g., [2–6]), this being a useful tool in asserting structural

safety. Sih introduced the concept of the strain energy density factor S as the product of the strain energy density by a critical distance from the point of singularity [7]. In recent years, the local SED criterion [8–10] has been presented as a combination of Sih's point-wise criterion with Neuber's concept of elementary structural volume [11]. As developed in [8], the local SED criterion is based on the strain energy density averaged over a control volume surrounding the notch tip. In plane problems, the control volume becomes a circle or a circular sector with a radius R_c in the case of cracks or pointed V-notches in mode I or mixed, I + II, mode loading (Fig. 1, *a* and *b*) [9].

Fig. 1. Control volume (area) for sharp V-notch (a), crack (b) and blunt V-notch (c) under mode I loading

The SED approach is based on the idea that under tensile stress, failure occurs when the mean value of the elastic strain energy referred to an area W is equal to the critical value W_c , which varies from material to material [8]. According to Lazzarin–Zambardi [8], if the material is ideally brittle, the value of the critical strain energy density follows:

$$W_c = \frac{\sigma_t^2}{2E}, \quad (1)$$

where σ_t is the ultimate tensile strength and E is the Young's modulus. When the notch opening angle is zero $2\alpha = 0$, the material critical radius R_c can be expressed in terms of the fracture toughness K_{Ic} , the ultimate tensile strength σ_t , and Poisson's ratio ν [12]:

$$R_c = \frac{(1+\nu)(5-8\nu)}{4\pi} \left(\frac{K_{Ic}}{\sigma_t} \right)^2 \text{ for plane strain}, \quad (2)$$

$$R_c = \frac{5-3\nu}{4\pi} \left(\frac{K_{Ic}}{\sigma_t} \right)^2 \text{ for plane stress}. \quad (3)$$

In the case of blunt notches, the total strain energy can be determined over the crescent shape volume (Fig. 1, c) and then the mean value of the SED can be expressed in terms of the elastic maximum notch stress $\sigma_{\max}$ [13]. By applying this condition, the total strain energy can be obtained over the area Ω (Fig. 1), and the corresponding mean value of the SED follows equation [9]:

$$\bar{W} = F(2\alpha)H\left(2\alpha, \frac{R_c}{\rho}\right) \frac{\sigma_{\max}^2}{E}, \quad (4)$$

where $F(2\alpha)$ depends on the notch opening angle, H varies

with the notch geometry $(2\alpha, R_c/\rho)$ and $\sigma_{\max}$ is the maximum elastic stress at the notch tip. Table 1 gathers different values of the H function for U-shaped notches $2\alpha = 0$ [9].

With all of this, the aim of the present research is to estimate the critical load on U-notched short glass fibre reinforced polyamide 6 (SGFR-PA6) by applying the strain energy density criterion. In order to simplify the calculations, the local SED approach explained above is applied. Moreover, as shown below, and due to the non-ideally brittle behaviour of SGFR-PA6, this methodology will be combined with the consideration of the whole (elastic-plastic) absorbed energy of the material (i.e., the total area under the stress–strain curve) so as to provide more accurate predictions.

In recent papers [14, 15], the analysed experimental programme has been used for both the prediction of the notch effect (by the direct application of the theory of the critical distances [16]) and the validation failure assessment validates a structural integrity assessment methodology (based on the use of failure assessment diagrams and the notch effect corrections provided by the line method, respectively).

2. Materials and methods

The experimental programme has been applied to short glass fibre reinforced polyamide 6 (SGFR-PA6) with four

Fig. 2. Tensile (a) and single-edge notch bend test specimens (b). All dimensions are in mm. Thickness is 4 mm, ρ varying from 0 to 2 mm

Table 1

Values of the function H when $2\alpha = 0$ for blunted V-shaped notches (coefficients determined numerically with $\rho = 1$ mm) [9]

R_c/ρ	$\nu = 0.30$	$\nu = 0.35$	$\nu = 0.40$
0.01	0.5638	0.5432	0.5194
0.05	0.5086	0.4884	0.4652
0.10	0.4518	0.4322	0.4099
1.00	0.1314	0.1217	0.1110

Table 2

SGFR-PA6 tensile parameters (average values). E —elastic modulus, $\sigma_{0.2}$ —proof stress, σ_t —ultimate tensile strength, $e_{\max}$ —strain under maximum load, ν —Poisson's number (x refers to the longitudinal direction)

Fibre content, %	E_{xx} , GPa	$E_{yy} = E_{zz}$, GPa	$\sigma_{0.2,x}$, MPa	$\sigma_{t,x}$, MPa	$e_{\max,x}$, %	$\nu_{xy} = \nu_{xz}$	$\nu_{yx} = \nu_{zx}$	$\nu_{yz} = \nu_{yz}$
5	3.30	3.00	66.90	72.05	2.67	0.39	0.35	0.45
10	3.55	3.15	70.15	78.15	2.84	0.38	0.34	0.46
30	6.45	4.00	105.35	128.00	3.56	0.34	0.21	0.58
50	12.60	5.48	161.15	192.80	2.47	0.30	0.13	0.66

different amounts of fibre content (5, 10, 30 and 50 wt %). Currently, short fibre reinforced thermoplastics are one of the most widely used technical plastics which are standing in for metal parts in engineering components due to their easy fabrication and good mechanical properties [17]. Adding short glass fibres to PAs leads to a higher heat distortion temperature, strength, abrasion resistance and stiffness, despite the fact that properties can be anisotropic (including mould shrinkage, which implies potential distortion) [18]. Regarding PA6—unlike many polymers—this is accomplished without any loss of impact strength, but strain at maximum load is reduced substantially [19]. The extensive use of these materials makes it essential to study their behaviour when containing stress risers which may appear and endanger the structural integrity of the corresponding component. With this purpose, five different notch radii were covered in the present research: 0 (crack-like defects), 0.25, 0.50, 1.00, and 2.00 mm.

The core of the experimental programme is composed of 108 specimens of SGFR-PA6. They were made by injection moulding with the short glass fibres (300 μm length and 10 μm diameter) oriented parallel to the longitudinal axis of the specimens. After injection molding, the mean thickness fibre orientation is 83° [20] and the effective fibre length is $204.2 \pm 40.9 \mu\text{m}$ [20, 21]. The geometry and dimensions are shown in Fig. 2, *a*. The specimens were dried in an oven at 100°C before testing (tensile or fracture) in order to proceed without moisture. The main mechanical properties were obtained following ASTM D638 [22] as the average values of two tensile tests per fibre content and

orientation. The results are shown in Table 2. Figure 3 gathers one stress–strain curve per fibre content. It can be observed that the higher the fibre content, the lower the linearity of the curve.

Five single-edge notch bend (SENB) specimens were tested per combination of the 5 notch radii and the 4 fibre contents (i.e., 100 total) following ASTM D5045-99 [23]. These fracture specimens were obtained from the central part of the corresponding tensile samples, the geometry being shown in Fig. 2, *b*. The notches were obtained by machining perpendicularly to the longitudinal direction of the original specimens. Only one test was invalid (30 wt %, notch radius 0.5 mm). Tables 3–6 gather the maximum load (fracture load) reached for each fibre content varying the notch radii. Figure 4 shows some examples of the curves obtained, with certain nonlinearity in those with higher fibre content. On the other hand, on five SENB specimens per fibre content, a crack-like defect ($\rho = 0 \text{ mm}$) was generated by sawing a razor blade. These specimens were used to derive the corresponding fracture toughness (K_{Ic} , see Table 7), which follows equation [23]:

$$K_{Ic} = \left(\frac{P_{\max}}{BW^{1/2}} \right) 6 \left(\frac{a}{W} \right)^{1/2} \times \frac{1.99 - a/W(1 - a/W)(2.15 - 3.93a/W + 2.7(a/W)^2)}{(1 + 2a/W)(1 - a/W)^{3/2}}. \quad (5)$$

3. Estimation of fracture loads

The assessment of the critical load on short glass fibre reinforced polyamide 6 (SGFR-PA6) is here analysed through the application of the strain energy density criterion [9]. By applying this criterion, it is straightforward to obtain the critical strain energy referred to an area, W_c (Eq. (1)), from the mechanical properties gathered in Table 2.

In order to derive the elastic maximum notch stress from Eq. (4), the different SED criterion parameters should be defined. The F factor value depends on the notch opening angle and, in the case of U-blunt notches with $2\alpha = 0$, F is equal to 0.785 [9]. In order to obtain the H function, it is necessary to define the material critical radius (Eqs. (2) and (3)). It should be mentioned that when the fracture resistance K_{mat} , associated to particular material and notch radius, is under the limit established by Eq. (6) [24], it may

Fig. 3. Strain-stress curves of SGFR-PA6: fibre content 5 (1), 10 (2), 30 (3), 50 wt % (4)

Table 3

Description of SGFR-PA6 notched specimens and maximum load obtained (5 wt %)

Notch radius ρ , mm	Specimen	Maximum load P_{exp} , N	Notch radius ρ , mm	Specimen	Maximum load P_{exp} , N
0.25	5-0.25-1	83.80	1.00	5-1-1	120.70
0.25	5-0.25-2	82.20	1.00	5-1-2	99.30
0.25	5-0.25-3	111.00	1.00	5-1-3	119.10
0.25	5-0.25-4	56.40	1.00	5-1-4	122.20
0.25	5-0.25-5	77.10	1.00	5-1-5	106.00
0.50	5-0.5-1	100.10	2.00	5-2-1	151.60
0.50	5-0.5-2	108.40	2.00	5-2-2	135.40
0.50	5-0.5-3	96.00	2.00	5-2-3	126.60
0.50	5-0.5-4	100.60	2.00	5-2-4	149.70
0.50	5-0.5-5	82.70	2.00	5-2-5	125.90

Table 4

Description of SGFR-PA6 notched specimens and maximum load obtained (10 wt %)

Notch radius ρ , mm	Specimen	Maximum load P_{exp} , N	Notch radius ρ , mm	Specimen	Maximum load P_{exp} , N
0.25	10-0.25-1	93.10	1.00	10-1-1	124.10
0.25	10-0.25-2	105.20	1.00	10-1-2	116.50
0.25	10-0.25-3	104.50	1.00	10-1-3	141.00
0.25	10-0.25-4	87.80	1.00	10-1-4	125.00
0.25	10-0.25-5	78.60	1.00	10-1-5	119.70
0.50	10-0.5-1	116.20	2.00	10-2-1	173.80
0.50	10-0.5-2	102.10	2.00	10-2-2	166.70
0.50	10-0.5-3	93.40	2.00	10-2-3	167.30
0.50	10-0.5-4	111.10	2.00	10-2-4	146.40
0.50	10-0.5-5	97.70	2.00	10-2-5	153.40

Table 5

Description of SGFR-PA6 notched specimens and maximum load obtained (30 wt %)

Notch radius ρ , mm	Specimen	Maximum load P_{exp} , N	Notch radius ρ , mm	Specimen	Maximum load P_{exp} , N
0.25	30-0.25-1	237.80	1.00	30-1-1	231.60
0.25	30-0.25-2	220.20	1.00	30-1-2	251.50
0.25	30-0.25-3	202.50	1.00	30-1-3	287.90
0.25	30-0.25-4	216.40	1.00	30-1-4	302.60
0.25	30-0.25-5	205.40	1.00	30-1-5	246.60
0.50	30-0.5-1	207.10	2.00	30-2-1	305.80
0.50	30-0.5-2	252.40	2.00	30-2-2	284.20
0.50	30-0.5-3	251.80	2.00	30-2-3	269.00
0.50	30-0.5-4	—	2.00	30-2-4	263.70
0.50	30-0.5-5	243.30	2.00	30-2-5	318.30

be considered that plane strain conditions are dominant. In this case, the R_c solution for the tested specimens is given by Eq. (2). The fracture resistance is here understood as the material resistance to fracture for a given notch radius,

in stress intensity factor units. On the other hand, when K_{mat} values are over the limit established by Eq. (7) [24] it may be assumed that plane stress conditions are dominant and the R_c solution follows Eq. (3):

Table 6

Description of SGFR-PA6 notched specimens and maximum load obtained (50 wt %)

Notch radius ρ , mm	Specimen	Maximum load P_{exp} , N	Notch radius ρ , mm	Specimen	Maximum load P_{exp} , N
0.25	50-0.25-1	322.00	1.00	50-1-1	389.70
0.25	50-0.25-2	338.00	1.00	50-1-2	394.50
0.25	50-0.25-3	329.40	1.00	50-1-3	402.40
0.25	50-0.25-4	360.60	1.00	50-1-4	395.70
0.25	50-0.25-5	335.00	1.00	50-1-5	389.60
0.50	50-0.5-1	367.40	2.00	50-2-1	432.30
0.50	50-0.5-2	367.90	2.00	50-2-2	414.20
0.50	50-0.5-3	364.60	2.00	50-2-3	426.50
0.50	50-0.5-4	376.90	2.00	50-2-4	431.00
0.50	50-0.5-5	380.10	2.00	50-2-5	427.00

plane strain limit

$$K_{mat} = \sigma_y \left(\frac{B}{2.5} \right)^{1/2}, \quad (6)$$

plane stress onset

$$K_{mat} = \sigma_y (\pi B)^{1/2}, \quad (7)$$

where B is the thickness of the specimen, and σ_y is the yield strength. In practice, the fracture toughness values can be located between the limits established by Eqs. (6) and (7). For this situation, the R_c solution has been obtained here by interpolating equations (2) and (3).

Table 1 gathers different H values for some combinations of $(R_c/\rho, \nu)$ when $2\alpha = 0$. For each combination of $(R_c/\rho, \nu)$ the coefficients H are obtained by interpolation. Once all the parameters are known, the proposal here is to combine the SED criterion for brittle materials with the simplified approach proposed in [9, 10]. The complete analytical description can be found in [25]. Then, the maximum notch stress σ_{max} is derived from Eqs. (1) and (4) as follows:

$$\sigma_{max} = \sqrt{\frac{\sigma_t^2}{2 \times 0.785 H (2\alpha = 0, R_c/\rho)}}. \quad (8)$$

Table 8 gathers the values obtained for the different parameters and for the different combination of fibre content and notch radius: the critical radius R_c , the H factor values, the critical value of the elastic strain energy W_c and the corresponding maximum notch tip stresses σ_{max} . Finite elements simulations have been performed with ANSYS to obtain the critical load P_{SED} , which is that one applied on the specimens generating σ_{max} at the corresponding notch tip. The modelling has considered the anisotropy of the material being analysed, with specific properties in width, height and longitudinal directions. Furthermore, the simulation was conducted in purely linear-elastic conditions.

Figure 5, *a* shows the comparison of the SED prediction P_{SED} with the experimental results P_{exp} . The experimental data used for each combination of fibre content and notch radius are the average value of those gathered in Tables 3–6. A strong conservatism of the analysis performed can be observed: the relations between the results predicted P_{SED} and those obtained experimentally P_{exp} are well below 1. In addition, the higher the fibre content, the lower the accuracy of the model proposed.

The stress-strain analysis assumes fully linear-elastic behaviour of the material in the tensile curve. However, Figure 3 showed evident nonlinearity for the four different materials (four different fibre contents). Hence, the assump-

Fig. 4. Load–displacement curve obtained in some SGFR-PA6 specimens for a fibre content of 10 wt %, $\rho = 0.00$ (1), 0.25 (2), 0.50 (3), 1.00 (4), 2.00 (5) (a); for a notch radius of 0.50 mm, fibre content 5 (1), 10 (2), 30 (3), and 50 wt % (4) (b)

Table 7

Description of SGFR-PA6 cracked specimens and corresponding values of K_{Ic} ($\rho = 0$ mm, crack-like defect)

Specimen	K_{Ic} , MPam ^{1/2}	$K_{Ic,av}$, MPam ^{1/2}	Specimen	K_{Ic} , MPam ^{1/2}	$K_{Ic,av}$, MPam ^{1/2}
5-0-1	2.40	1.84	30-0-1	5.76	4.77
5-0-2	1.64		30-0-2	4.74	
5-0-3	1.78		30-0-3	4.90	
5-0-4	1.65		30-0-4	4.01	
5-0-5	1.73		30-0-5	4.44	
10-0-1	2.46	2.13	50-0-1	8.09	8.59
10-0-2	2.28		50-0-2	8.67	
10-0-3	1.65		50-0-3	8.56	
10-0-4	1.81		50-0-4	8.66	
10-0-5	2.47		50-0-5	8.96	

Table 8

SED parameters for the different approaches proposed and for each combination of fibre content and notch radius

Fibre content, %	Notch radius ρ , mm	R_c , mm	R_c/ρ	H	W_c , MPa	σ_{max} , MPa	W'_c , MPa	σ'_{max} , MPa
5	0.25	0.136	0.542	0.190	0.79	132.08	1.09	155.49
	0.50	0.136	0.271	0.289		106.89		125.83
	1.00	0.164	0.164	0.360		95.84		112.82
	2.00	0.271	0.135	0.384		92.79		109.23
10	0.25	0.160	0.640	0.170	0.86	151.37	1.31	186.80
	0.50	0.160	0.320	0.269		120.28		148.43
	1.00	0.201	0.202	0.336		107.52		132.69
	2.00	0.387	0.194	0.342		106.64		131.60
30	0.25	0.400	1.599	0.124	1.27	290.52	3.06	450.95
	0.50	0.462	0.925	0.132		281.69		437.24
	1.00	0.567	0.567	0.198		229.38		356.04
	2.00	0.702	0.351	0.269		196.94		305.69
50	0.25	0.571	2.286	0.131	1.48	424.48	3.13	618.34
	0.50	0.630	1.260	0.131		424.48		618.34
	1.00	0.685	0.685	0.180		362.42		527.93
	2.00	0.785	0.393	0.264		299.30		435.99

tion of the linear approach (SED criterion) is not adequate for this type of material.

Thus, another methodology is here proposed to increase the accuracy of the fracture load prediction. The analysis performed will consider the whole area under the stress-strain (i.e., the total absorbed energy W'_c). Once the area is obtained, the corrected maximum notch stress σ'_{max} follows:

$$\sigma'_{max} = \sqrt{\frac{EW'_c}{0.785H(2\alpha = 0, R_c/\rho)}}. \quad (9)$$

The estimation of the new fracture loads P'_{SED} was finally obtained by repeating the finite element analysis (i.e., obtaining the load that generates the corresponding σ'_{max} at the notch tip). Table 8 shows the different values of W'_c and σ'_{max} obtained, while Fig. 5, *b* compares the predictions of the fracture load P'_{SED} with the experimental results P_{exp} . As shown in Fig. 3, the loss of linearity in the behaviour of tensile specimens is higher when the fibre content increases. Hence, the difference between W_c and W'_c and therefore, between σ_{max} and σ'_{max} , increases with the fibre content

Fig. 5. Comparison of the critical load values obtained with W_c (a) and W'_c (b) experimental data

(given that the situation deviates from linear-elastic conditions). By applying this second approach, a clear reduction in the conservatism of the results can be observed. The prediction is accurate not only for high fibre contents but also for low fibre contents. Comparing the fracture loads predicted with the experimental results obtained, the relation is close to 1. Thus, the range of accuracy is much higher here than that observed when notches are treated as cracks and comparable to that obtained through other approaches such as the theory of critical distances [e.g., 14, 26, 27] or the combination of the TCD and failure assessment distances [15, 28, 29]. Summing up, the application of this approach to this type of material is, therefore, both simple and safe.

4. Conclusions

This paper provides and validates a methodology for the assessment of fracture loads in notched specimens of short glass fibre reinforced polyamide 6 (SGFR-PA6) using the strain energy density criterion. The core of the experimental programme is composed of 100 fracture (SENB) specimens combining different notch radii (from 0 up to 2 mm) and different fibre contents (from 5 up to 50 wt %).

The initial assessment, which assumes linear-elastic behaviour, predicts fracture loads that are far from the results obtained experimentally. Given that SGFR-PA6 develops an elastic-plastic behaviour, another methodology has been proposed considering the whole absorbed energy in the

tensile test (elastic-plastic area under the stress-strain curve). With this new approach, the estimation of the critical load is closer to the results obtained within the experimental programme. The prediction of fracture loads on SGFR-PA6 using the methodology proposed gives accurate results, closer to the physics of the problem. Therefore, the local approach is again shown as a powerful tool in fracture assessment.

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