DETERMINATION OF THE FRACTURE TOUGHNESS IN WOVEN-PLY CARBON FIBERS POLYPHENYLENE SULFIDE THERMOPLASTIC COMPOSITES AT TEMPERATURES HIGHER THAN GLASS TRANSITION TEMPERATURE

M. Chabchoub[1,2], B. Vieille[1], C. Keller[1], M. Beyaoui[2], M. Taktak[2], M. Haddar[2], L. Taleb[1]

[1]INSA Rouen – Groupe de Physique des Matériaux UMR 6634 CNRS, 76801 St Etienne du Rouvray, France
[2]ENI Sfax – Laboratory of Mechanics, Modelling and Production, route Soukra, 3038 Sfax, Tunisie
Tel.: (0033) 232 959 756 – Fax: (0033) 232 959 704
* Address correspondence to: Manel.Chabchoub@insa-rouen.fr

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Abstract
This study was aimed at investigating the crack initiation and propagation in a 5-harness satin weave carbon fabric reinforced PolyPhenylene Sulphide (PPS) with quasi-isotropic stacking sequence. The tested notched specimens are characterized by an elastic-brittle response resulting from transverse matrix cracking and fiber breakage near the notch tip. From macroscopic response standpoint, transverse crack initiation and propagation virtually occur at the same time corresponding to ultimate failure making therefore difficult the assessment of corresponding strain energy release rates. Thus, crack initiation and propagation was investigated by means of different methods: the crack opening displacement (COD) method and cracking gauge were considered for crack initiation, whereas the compliance-based beam method was considered for crack propagation. Reproducible results were obtained and compared from these methods applied to TP-based composites in order to investigate the mode I crack growth at $T>T_g$ when matrix toughness in enhanced. Finally, based on Linear Elastic Fracture mechanics (LEFM), the fracture toughness K_{Ic} was calculated for quasi-isotropic laminate from the critical strain energy release rate G_{Ic}.

1. Introduction

Over the last five decades, researchers have became greatly interested in structural failure investigation. Fracture mechanics plays now an increasingly important role not only for academic interest but also for structural design as it provides valuable data during the design process. Fracture mechanics is usually characterized by many parameters (e.g. fracture toughness) that can be obtained from different experimental techniques. A comprehensive review of techniques for the experimental characterization of the fracture toughness associated with the translaminar failure modes of fiber-reinforced polymers (FRPs) is presented in [1]. Translaminar fracture toughness is important to characterize the failure resistance and response of notched composite structures [2]. However, it has received relatively little attention from the scientific community until now [3]. In FRPs, the fracture mechanics behavior is often studied by using the Linear Elastic Fracture Mechanics (LEFM) parameters: the critical strain energy release rate (G_{Ic}) and stress intensity factor (K_{Ic}), the J-integral, the crack opening displacement and the R-curve analysis [4]. In fracture mechanics, the energy release rate G is one of the most fundamental parameters. It is defined as the rate of energy released by the crack growth. An important aspect of fracture resistance is that it may vary as the crack grows such that G is a function of the crack growth Δa [5]. Early in the sixties, Sih et al. examined the nature of the local crack-tip stress field in anisotropic bodies [6]. They proposed a method to determine the stress-intensity factors K_i which can be related to the energy release rates G_i (i=1,2,3). As it was

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introduced by Sih et al., the stress-intensity factors or the fracture toughness K_i represent physically the intensity of the linear-elastic stress distribution, due to the introduction of a crack into the body, surrounding a crack-tip. It is therefore assumed that small amounts of nonlinearity (e.g. plastic deformation) at the crack-tip are embedded within the field, and do not significantly disturb it [7].

Among the different experimental techniques developed over the years to quantify the fracture toughness of materials, the compliance method has been successfully applied to fiber-reinforced polymer composites [4-8]. The purpose of the present work is to investigate the crack initiation and propagation in a 5-harness satin weave carbon fabric reinforced PolyPhenylene Sulphide (PPS) with quasi-isotropic stacking sequence characterized by an elastic-brittle response. Once they are initiated, cracks will propagate very rapidly until ultimate failure. Indeed, in the ideal case (linear elastic-brittle response), an abrupt drop in load at the moment of crack initiation occurs. Since it is difficult to precisely measure the length of the crack at the peak load (and therefore the compliance) in the polymer composites, COD measurements are often used to investigate the crack initiation and to estimate the strain energy release rate corresponding to crack initiation G_{Iinit} [4]. Therefore, different methods have been used: the crack opening displacement (COD) method and cracking gauge were considered for initiation, whereas the compliance-based method was considered for propagation. These methods show their capacities to investigate the mode I crack growth and to evaluate the fracture toughness for crack initiation and propagation in high-performance TP composites under high-temperature services conditions when TP matrix toughness in enhanced (120°C>T_g).

2. Materials and experimental set-up

2.1 Materials

The studied composite materials are carbon fabric reinforced laminates consisting of a semi-crystalline high-performance PPS supplied by the Ticona company [9-10-11-12]. The woven-ply prepreg, supplied by SOFICAR, consists of 5-harness satin weave carbon fiber fabrics (T300 3K 5HS) whose volume fraction is 50%. The prepreg plates are hot pressed according to the following quasi-isotropic lay-up: [(0,90)/(±45)/(0,90)/(±45)/(0,90)/(±45)/(0,90)]. The glass transition temperature of this material is about 107°C.

2.2 Method and experimental set-up

All the tests were performed using a 100kN capacity load cell of a MTS 810 servo-hydraulic testing machine in displacement-controlled mode and with a temperature control system. Tensile loadings were applied to Single-Edge Notch (SEN) specimens at 120°C (see Fig. 3) [5-13-14]. SEN specimens have different ratio a/w (ranging from 0.1 to 0.6) of the initial crack length over the specimen width. In addition, damage mechanisms have been discussed by means of fractographic analyses: macroscopic observations by means of an optical microscope and scanning electron microscope (SEM) observations with a Leo 1530 Gemini Zeiss microscope. Three specimens were tested in each configuration. Finally, the specimen was instrumented on one side by a crack propagation gauge (HBM crack gauge-type RDS22) which cover the whole bonding length and monitor crack initiation and propagation during the mechanical test. The crack gauges included 50 parallel links with a pitch of 0.1mm. As the crack propagated under the crack propagation gauges, the links were progressively broken and the electrical resistance of the gauge was increased.

3. Results and discussion

3.1 Translaminar fracture toughness measurement

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The tested notched specimens are characterized by an elastic-brittle response (see Fig. 1) as the tensile thermo-mechanical behavior of quasi-isotropic laminates is mostly driven by the tensile response of 0° oriented fibers. The elastic-brittle mechanical response primarily results from the transverse matrix cracking and fibre breakage near the notch tip (see Fig. 2). In quasi-isotropic specimens, transverse crack initiation and propagation virtually occur at the same time corresponding to ultimate failure. The observation of fracture surfaces also show a few bare fiber bundles in the ±45° direction along specimens' free edges, due to fiber-matrix debonding and even fiber bundles pull-out.

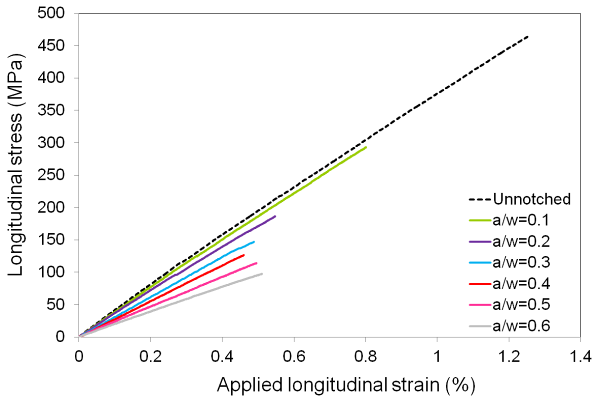

Figure 1. Tensile responses of SEN quasi-isotropic C/PPS specimens at 120°C: influence of the ratio a/w of the initial crack length over the specimen width.

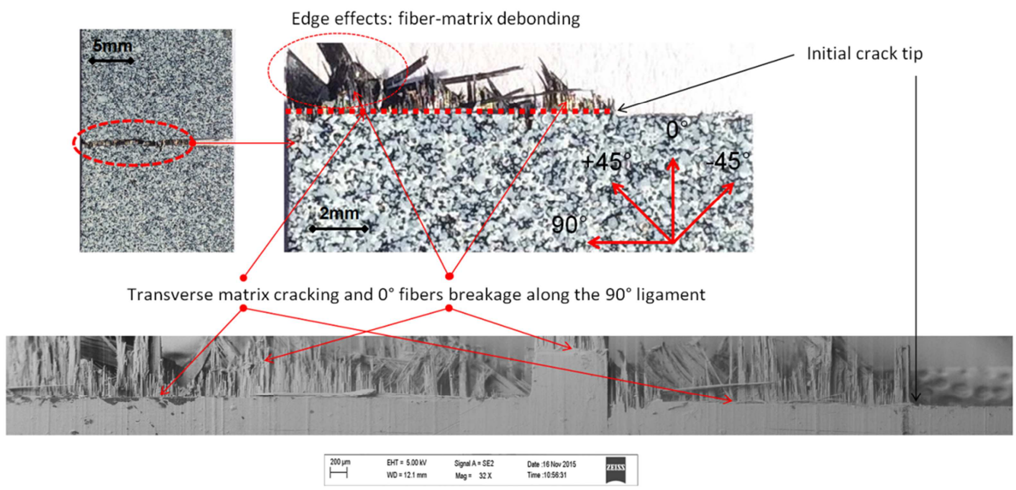

Figure 2. Macroscopic and SEM observations of fracture surface for SEN quasi-isotropic C/PPS specimens subjected to tensile loadings at 120°C.

3.1.1 Transverse crack initiation

In order to investigate the crack initiation and to estimate the strain energy release rate G_{Iinit} at damage onset, COD measurements are used. Indeed, for materials that exhibit stable crack growth prior to failure, the COD method provides toughness values for cracks initiation (see Fig. 4) as the

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crack is driven stably into the fracture process zone caused by an increase in the applied loads (see Fig. 5).

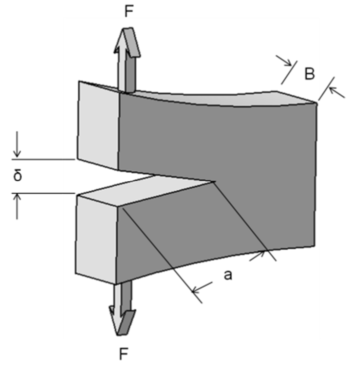

Figure 3. Double cantilever beam (DCB) method

In the case of SEN specimens, the strain energy release rate can be evaluated directly from the application of double cantilever beam method (see Fig. 3) to the mechanical tests data:

$$G_I(X,A) = -\frac{\partial\Psi}{\partial A} = \frac{12F^2a^2}{EB^2h^3} = \frac{3\delta F}{2aB} \tag{1}$$

where δ is the crack opening displacements, F is the applied load, B is the specimen thickness, h is the specimen width, a is the notch length evolution and E is the axial stiffness. The crack opening displacements δ is defined as the total separation of the crack faces, and can be measured directly by in-situ Digital Image Correlation from gradually loaded SEN specimens. Then, based on LEFM, the fracture toughness K_{Iinit} was calculated from the following expression established for plane stress conditions [15], the latter assumption being verified in the case of thin laminates:

$$K_I = \sqrt{E(1-\nu^2)G_I} \tag{2}$$

where E is the longitudinal stiffness and ν is the Poisson's ratio.
In addition, different approximations have been proposed for K_I in the literature [7], and the stress intensity factor can be classically expressed as follows for SEN specimens:

$$K_I = \sigma\sqrt{\pi a}.F\left(\frac{a}{w}\right) \tag{3}$$

where σ is the applied stress, a denotes the length of the initial crack and w is the specimen width. $F(a/w)$ is a finite-width-correction (FWC) factor calculated from the ratio a/w and empirical formulas. By definition, this FWC factor is a scale factor applied to multiply the notched infinite-plate solution to obtain the notched finite-plate result [16]. For example, Gross et al. have proposed the following expression for SENT specimens [17], whose precision is 0.5% for $a/w \leq 0.6$:

$$F(a/w) = 1.122 - 0.231*(a/w) + 10.550*(a/w)^2 - 21.710*(a/w)^3 + 30.382*(a/w)^4 \tag{4}$$

The COD method provides an estimation of the remote applied stress at crack onset. It was estimated as about 140 MPa.m$^{1/2}$ (Figs. 4 and 5). Thus the values for fracture toughness at crack initiation were determined for a ratio a/w=0.3: 28.32 MPa.m$^{1/2}$ from (Eq. 1) and 27.92 MPa.m$^{1/2}$ from semi-empirical expression (Eq. 3) given by Tada for isotropic materials respectively, hence proving the capacity of COD method to determine initiation fracture toughness value for quasi-isotropic laminates at 120°C.

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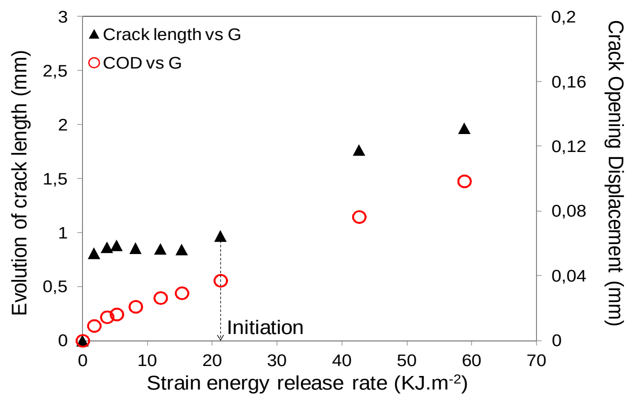

Figure 4. Evolution of crack length and crack opening displacement as a function of strain energy release rate in quasi-isotropic laminates at 120°.

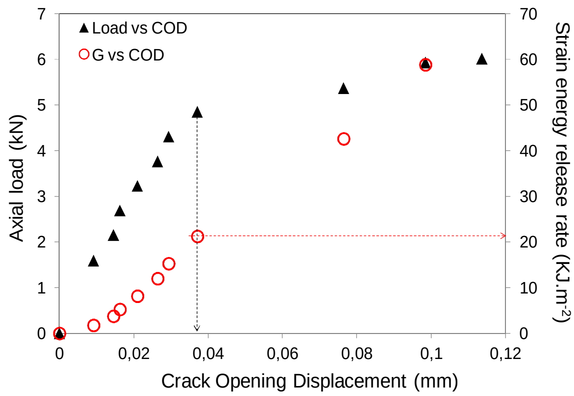

Figure 5. Evolution of axial load and strain energy release rate as a function of crack opening displacement in quasi-isotropic laminates at 120°.

Using crack propagation gauge to determine the remote stress, one can notice that, for QI laminates with a ratio a/w=0.3, the length of crack starts to increase at 152 MPa corresponding to crack initiation (see fig. 6). From Eq. 3, the fracture toughness value was determined as 31.2 MPa.m$^{1/2}$. The comparison between the methods used to estimate the crack onset in QI laminates shows that the toughness value obtained using cracking gauge method is closed to those obtained using COD and semi-empirical expression given by Tada for isotropic materials.

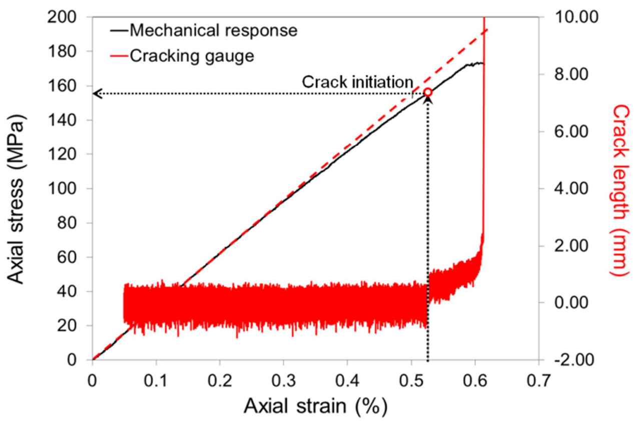

Figure 6 . Mechanical response and identification of remote applied stress at crack initiation using a cracking gauge.

3.1.2 Transverse crack propagation

In order to calculate the translaminar fracture toughness for crack propagation, the compliance method has been applied to quasi-isotropic (QI) SEN specimens with different initial crack lengths. The compliance C is defined by the slope of the load-displacement curve which is usually linear [4-8]. Indeed, the use of LEFM requires a linear load-displacement behavior and very localized plastic

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deformation at the crack tip. The later condition seems to be satisfied in quasi-isotropic laminates considering the fracture surfaces discussed in the above Section. As the mechanical response of QI laminates appears to be quasi elastic-brittle, the relationship between the compliance and the crack length a can be classically associated with the calculation of the critical strain energy release rate G_{Ic} by the following expression:

$$G_{Ic} = \frac{P_{max}^2}{2B}\frac{dC}{da} \tag{5}$$

In (Eq. 5), B is the thickness of the laminate and P_{max} is the maximum load at failure. The compliance can be obtained for different initial crack lengths (see Fig. 7). From (Eq. 5), it is possible to compute the critical strain energy release rate in mode I. and from (Eq. 2), to deduce the fracture toughness K_{IC}.

As the ratio a/w increases from 0.1 to 0.4, it appears that the fracture toughness linearly increases to reach a maximum value at about 37 MPa.m$^{1/2}$ where it starts decreasing (see Fig. 9). It might be explained by mixed failure modes resulting from important edge effects (fiber/matrix debonding and fiber bundles pull-out) in specimens with high initial crack lengths. At the same time, the residual tensile strength decreases. For a ratio a/w=0.3, the crack propagation fracture toughness has been estimated as about 35 MPa.m$^{1/2}$ which is higher than the crack initiation fracture toughness.

In addition, the fracture toughness values calculated for quasi-isotropic laminates can be compared to the values obtained for isotropic materials (see Fig. 8), from semi-empirical expressions established by different authors [7], as defined by (Eq. 3) in Section 3.1.1. From Fig. 8, it can be observed that the average values are virtually the same: 34 MPa.m$^{1/2}$.

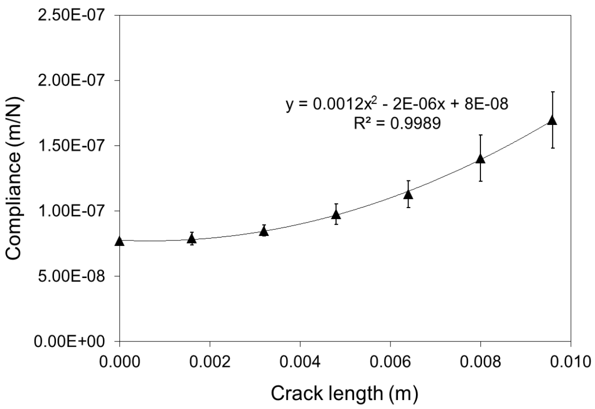

Figure 7. Evolution of compliance as a function of the initial crack length for SEN quasi-isotropic C/PPS specimens subjected to tensile loadings at 120°C.

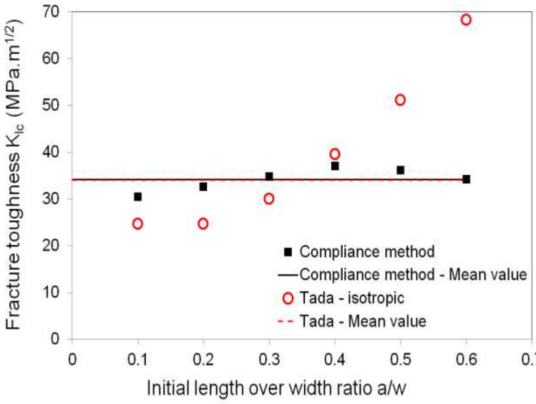

Figure 8. Comparison of fracture toughness values as a function of the ratio a/w of the initial crack length over the specimen width for quasi-isotropic C/PPS laminates obtained from compliance method and semi-empirical formula proposed for SEN isotropic specimens [7].

Furthermore, the expression of σ_y at the crack tip can be used to estimate the stress concentration factor K_T for Mode-I type loading as it is defined by the ratio $\sigma_y(\theta = 0)\big|_{x=0}/\sigma$ where σ is the remote applied stress far from the singularity such as [6]:

$$\sigma_y(\theta = 0)\big|_{x=0} = \frac{K_I}{\sqrt{2\pi r}} \tag{6}$$

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where $r = 0.085$ mm is the radius of the notch at the crack tip.
Substituting (Eq. 3) into (Eq. 6), one can obtain at the crack tip ($\theta = 0, x = 0$):

$$\sigma_y(\theta = 0)\big|_{x=0} = \frac{\sigma\sqrt{\pi a}.F(a/w)}{\sqrt{2\pi r}} \tag{7}$$

From which the stress concentration factor K_T can be deduced:

$$K_T = \frac{\sigma_y(\theta=0)\big|_{x=0}}{\sigma} = \sqrt{\frac{a}{2r}}.F(a/w) \tag{8}$$

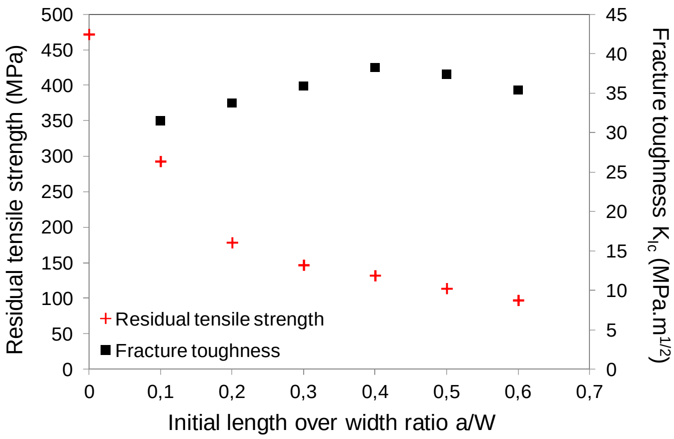

Figure 9. Changes in the residual tensile strength of SEN specimens and critical fracture toughness K_{IC} as a function of the ratio a/w of the initial crack length over the specimen width obtained from compliance-based method for quasi-isotropic C/PPS laminates at 120°C.

3. Conclusions

The purpose of this study was to investigate the mode I crack growth in quasi-isotropic carbon fibers woven-ply reinforced PolyPhenylene Sulphide (PPS) laminates. QI laminates are characterized by an elastic-brittle response resulting from transverse matrix cracking and fibre breakage near the notch tip. Even when they are subjected to high temperature contributing to the enhancement of PPS matrix ductility and toughness at T>T_g, in quasi-isotropic laminates, transverse crack initiation and propagation are virtually observed at the same time corresponding to ultimate failure. However, in reality, brittle materials exhibit stable crack growth prior to peak load. Thus, it was necessary to distinguish between fracture toughness corresponding to cracks initiation K_{Iinit} and cracks propagation K_{Ic}. Therefore, the crack opening displacement (COD) method and cracking gauges were considered for crack initiation, whereas the compliance-based method was applied to estimate the strain energy release rate corresponding to crack propagation for different initial crack lengths. Finally, based on LEFM, the fracture toughness or the critical stress intensity factor K_{Ic} was calculated for quasi-isotropic laminate from the critical strain energy release rate G_{Ic}. These methods proved their capacity to estimate fracture toughness for cracks initiation and propagation in quasi-isotropic C/PPS laminates. For the ratio a/w=0.3, the crack initiation fracture toughness values were determined as 28.32 MPa.m$^{1/2}$, 27.92 MPa.m$^{1/2}$ and 31.2 MPa.m$^{1/2}$ using COD method, semi-empirical expression given by Tada for isotropic materials and cracking gauge, respectively. However, the crack propagation fracture toughness values were determined for different ratio a/w, ranging from 0.1 to 0.6,

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using compliance beam method and they were compared to those obtained using semi-empirical expression given by Tada for isotropic materials. It was observed that the average values are virtually the same (34 MPa.m$^{1/2}$). Finally, in order to generalize these approaches for designing using LEFM, COD and cracking gauge methods should be applied for different notch length over specimen width ratio a/w.

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