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Critical Void Content for Polymer Composite Laminates

Michelle Leali Costa*
Instituto de Aeronáutica e Espaço, 12228-904 São José dos Campos, São Paulo, Brazil
Sérgio Frascino Müller de Almeida†
Instituto Tecnológico de Aeronáutica, 12228-900 São José dos Campos, São Paulo, Brazil
and
Mirabel Cerqueira Rezende‡
Instituto de Aeronáutica e Espaço, 12228-904 São José dos Campos, São Paulo, Brazil

An experimental program to characterize the effect of voids on the strength of composite laminates is presented, and the adequacy of a fracture criterion to represent the experimental data for the effect of voids on the compressive and interlaminar shear strength of composite laminates is assessed. The experimental program investigates the effect of the material system (epoxy matrix vs bismaleimide matrix), type of reinforcement (unidirectional tape vs woven fabric), and the type of loading (compression vs interlaminar shear) on the critical void content. Laminates produced with carbon fabric/epoxy, carbon tape/epoxy, and carbon fabric/bismaleimide were produced with an intentionally high void content. The ultrasonic absorption coefficient was measured for all specimens and shown to vary approximately linearly with the void content, with the exception of the carbon fabric/epoxy laminates that presented a bilinear relationship with void content, corroborating previous experimental results. The effects of these factors on the strength of composite laminates are discussed in terms of the fracture parameters involved in the fracture criterion. The critical void content is estimated for each case both in terms of void content and ultrasonic attenuation.

Introduction

A COMMON problem in the manufacturing of polymer composites is the formation of defects such as resin-rich regions, crimped and distorted fibers, foreign inclusions, and voids. Among those defects, voids are arguably the greatest problem[1] because they are difficult to avoid, particularly at the corners of composite components, and are detrimental to the mechanical properties.[2–7] Voids are formed for a number of reasons, including the formation of bubbles from volatile byproducts produced during the cure reaction of the polymeric matrix, the use of a high-viscosity resin combined with closely packed fibers that are not completely wetted by resin, the entrapment of air in the material system, and fabrication mishaps such as a leaking vacuum bag or a poor vacuum source.[2,5–8]

Most aircraft composite parts are inspected after fabrication with nondestructive techniques such as ultrasound either by pulse echo or through transmission. These techniques are able to detect defects that cause ultrasonic attenuation such as voids, delaminations, interlaminar cracks, inclusions, foreign object damage, resin-rich regions, and others.[2,3,7]

The behavior of composite laminate with voids under different types of mechanical loading has been widely studied. Most works consider the interlaminar shear strength,[2,7–13] but the interlaminar fracture toughness,[8] bending strength under static and fatigue loading,[7] and compressive strength[3,4] have also been studied. However, there is not a general agreement over the magnitude of the effect of porosity on the mechanical properties of composites. The difficulty lies in the large number of parameters involved in the problem. Different types of preimpregnated materials used in the manufacture of the laminates affect the material toughness; the processing parameters and the type of reinforcement affect the distribution, the location, the shape, and the size of the voids in the laminate. All of these factors, in turn, produce different effects on the laminate strength. The type of mechanical loading, its nature (static or fatigue), and the inspection technique used are also significant factors. For example, the use of different frequencies in the ultrasound equipment results in different values of attenuation. Therefore, only results obtained from the characterization of composites produced and tested in a similar way can be directly compared.

The experimental studies mentioned aim at correlating the void content to the laminate strength for a specific type of loading. In those studies, it is implicitly assumed that the void content is uniform at least over the critical section of the specimen. However, in practice, voids are not uniformly distributed but are random in nature. Note that void content is a measurement associated with a finite volume of material rather than measurement to a point. The void content measurement by either matrix digestion or ultrasonic inspection captures some sort of average value over a given volume, without retaining the information on the shape, size, and distribution of the voids. However, these features play an important role in determining the effect of voids on the mechanical behavior of the laminate and are primarily controlled by the matrix material, type of reinforcement, and the manufacturing problem that originated the defects. The important issue of the effect of the size of the area of the laminate affected by voids is not addressed in this work. The voids are assumed to be uniformly distributed over the laminate.

A fracture criterion that correlates fracture stress with void content or, alternatively, to the ultrasonic attenuation, is needed to establish an acceptance level for the inspection. Establishing the acceptable level of defects is a critical issue in designing composite structures. An overly conservative acceptance criterion causes many parts that could perform satisfactorily to be unnecessarily discarded, increasing manufacturing costs. On the other hand, if the deleterious effects of defects are underestimated, in-service failure of some parts may occur. Both situations are avoided by a judicious choice of acceptable level of defects in the part. This should be based on reliable fracture criteria supported by extensive experimental characterization and an in-depth understanding of the effect of defects on the mechanical behavior of the laminate.[2,3]

Almeida and Nogueira Neto[7] proposed a fracture criterion that presented good correlation with experimental data on the bending strength of composite laminates with voids. The same idea was

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*Research Scientist, Materials Division; mleali@directnet.com.br.
†Professor, Department of Mechanical Engineering; frascino@mec.ita.br.
‡Research Scientist, Materials Division; mirabel@iae.cta.br.

successfully applied to predict the interlaminar shear strength by Almeida and Santacreu[6] and Jeong.[5] The fracture criterion proposed by Almeida and Nogueira Neto[7] is based on the ultrasonic attenuation rather than directly using the void content. The rationale for this is that, in practical applications, the acceptable level of defects must be established in terms of a nondestructive technique. However, the laminate thickness, type of matrix, and reinforcement affect the shape and size of the voids and, consequently, the ultrasonic attenuation. Therefore, the void content corresponding to a given ultrasonic attenuation level depends on those factors; as a consequence, the fracture parameters obtained from the application of the fracture criterion will reflect the dependence of the ultrasonic measurements on those factors.

The purpose of this work is 1) to present the results of an experimental program to investigate the effect of voids on the compressive strength of composite laminates, 2) to assess the adequacy of the fracture criterion proposed by Almeida and Nogueira Neto[7] to represent the experimental data for the effect of voids on the compressive and shear strength of composite laminates, and 3) to discuss the effect of the material system (epoxy matrix vs bismaleimide matrix), type of reinforcement (unidirectional tape vs woven fabric), and the type of loading (compressive vs interlaminar shear) on the critical void content of composite laminates both in terms of volume fraction and ultrasonic attenuation. Moreover, the fracture parameters are estimated from the fracture criterion proposed by Almeida and Nogueira Neto,[7] and the effect of the aforementioned factors is discussed.

Experimental Procedure

Fabrication of the Specimens and Void Content Measurements

Three types of composite laminates were studied in this work: carbon fabric and unidirectional tape reinforced epoxy and carbon fabric reinforced bismaleimide (BMI). T300 fibers were used for all laminate sets. Fabric reinforced laminates were produced with eight-harness satin weave pre-impregnated fabric (prepreg) with epoxy resin (F584) or BMI resin (F652) supplied by Hexcel Composites. Table 1 lists the characteristics of the specimens manufactured to evaluate the effect of the matrix system, laminate thickness, and void content on the ultrasonic attenuation and compressive and interlaminar shear strength. Each specimen type is defined by the matrix material, type of reinforcement, and laminate thickness. A reference specimen of each specimen type was produced to represent the behavior of low void content laminates.

Polymer composites with high void content were manufactured using a procedure based on the rheological analyses of the wet prepregs.[2,3] Laminates presenting intentionally high porosity levels were produced, combining the technique proposed by Almeida and Nogueira Neto[7] and Olivier et al.[14] This procedure involved the control of the effective pressure on the liquid resin during cure with the simultaneous introduction of moisture between the layers during the layup, as suggested by Gürdal et al.[15] Moisture was introduced by spraying water finely and uniformly to produce laminate plates with homogeneous porosity. The effective pressure on the liquid resin and the amount of moisture dispersed into the laminate were used to control the void content.[16] All specimens were cured in an autoclave at 180°C with pressure of 0.71 MPa. The BMI specimens were post cured for 8 h at 232°C.

The fabric reinforced laminates were produced with either 8 or 11 plies, with the fabric warp direction aligned to the plate edges ($[0, 90]_8$ or $[0, 90]_{11}$ laminates). The resulting 8- and 11-ply carbon fabric/epoxy and carbon fabric/BMI laminates have 3.0- and 4.1-mm nominal thickness, respectively. Specimens manufactured with carbon/epoxy unidirectional tape were produced with either 10 or 14 layers, resulting in unidirectional laminates ($[0]_{10}$ or $[0]_{14}$ laminates) with 2.0- or 3.0-mm nominal thickness, respectively. The thicker specimens of each type were used for obtaining the interlaminar shear strength measurements reported by Costa et al.[2]; the thinner specimens were used to characterize the effect of voids on the compressive strength in the present work.

Table 1 Description of the specimens

Type of reinforcement	Laminate thickness, mm
Epoxy	
Fabric	4.1
	3.0
Unidirectional (tape)	3.0
	2.0
(BMI)	
Fabric	4.1
	3.0

All plates were ultrasonically inspected to assess the resulting distribution of porosities. Areas of uniform porosity within each plate were identified, and different levels of void and fiber content specimens and at least 10 interlaminar shear and compressive specimens were cut from each of those areas.

The manufacturing procedure just described was used to produce compressive strength specimens with intentionally high void content. Four different void content levels, ranging from 0.93 to 5.6% were obtained for carbon fabric/epoxy laminates. Also, four different void content levels ranging from 0.41 to 4.41% were produced with carbon tape/epoxy, and, finally, seven different void content levels ranging from 1.1 to 4.2% were obtained for the carbon fabric/BMI specimens. One additional plate for each type of resin system and reinforcement was produced using the standard manufacturing technique to establish a reference for a good-quality, low-porosity level plate. Void content specimens and compressive strength specimens were also cut from the reference plates.

The void content and volume fiber content of each area were measured by matrix digestion according to American Society for Testing and Materials (ASTM) 3171. The fiber and resin density used for the computations were provided by the manufacturer. The average value of the five measurements was taken as the nominal void content associated with each porosity level. The volume fiber content was between 62 and 72% for the carbon fabric/epoxy specimens, 64 and 69% for the carbon tape/epoxy, and between 64 and 70% for the carbon fabric/BMI specimens.

Ultrasonic Inspection

All plates were inspected with a 5-MHz ultrasonic failure detector by using the technique described in Ref. 2 to generate an actual size map of the plate, associating a color with each attenuation level. This feature was used to identify areas of constant porosity level.

The measured ultrasonic attenuation is the result three factors: front surface loss, transmission loss, and back surface losses. The front and back surface losses do not depend on the condition of the panel, apart from its surface finish, and would be expected to be independent on the plate thickness.[13] On the other hand, the transmission loss depends on the defects present in the laminate. A calibration procedure[2] was used to compensate for the front and back surface, such that the measured attenuation corresponds to the transmission losses through the specimen only.

The ultrasonic absorption coefficient α may be defined as

$$\alpha = A_t/t \tag{1}$$

where α is measured in decibels per millimeter and depends on the internal condition of the laminate, particularly on the void content, and where the transmission loss A_t (measured in decibels) is assumed to increase linearly with the plate thickness t.

Three independent scans of each plate were performed to measure the absorption coefficient of the selected areas with approximately uniform porosity level.

Interlaminar Shear Strength Tests

The results of the interlaminar shear strength (ILSS) tests, according to ASTM D2344, were reported in Ref. 2. There were 10 specimens of each type, with dimensions 24 × 6.35 × 4.1 or 3.00 mm³ (length times width times thickness), tested to assess the effect of void content on the ILSS. A nominal span length of 20-mm and a 6-mm-diam loading nose were used. The diameter of the supports was 3 mm. The tests were performed in an Instron mechanical testing machine using a test speed of 1.3 mm/min.

Compressive Strength Tests

A large number of relatively complex loading fixture and specimen configurations have been developed to measure the compressive strength of composites. A widely accepted test method, the Illinois Institute of Technology Research Institute compression test (ASTM D3410-87, 1987), employs a relatively short, unsupported test specimen and linear bearings and hardened steel shafts to ensure collinearity of the load path. The wedge grips rest in cavities machined in the upper and lower end blocks.[17] This method was used in the present work.

There were 10 specimens of each type, with dimensions $139.7 \times 12.7 \times 3.00$ mm^3 (length times width times thickness), tested to assess the effect of void content on the compressive strength. Glass/epoxy tabs 63.5 mm long were used, resulting in a gauge length of 12.7 mm. The tests were performed in an Instron mechanical testing machine.

Results

Ultrasonic Attenuation Properties of Polymeric Composites

Figures 1–3 correlate the void content determined by acid digestion (ASTM D3171) to the measured absorption coefficients α for all laminates studied. As expected, the smallest absorption coefficient (~0.11 dB/mm) correspond to the reference laminates. The absorption coefficients vary approximately linearly with void content for all cases. Few measurements could be made of very high void content laminates because of the difficulty in consistently obtaining laminates with a uniform distribution of voids for high void contents. However, the results of this work demonstrate that the range of void content obtained for all specimen types sufficed to determine the maximum allowable void content.

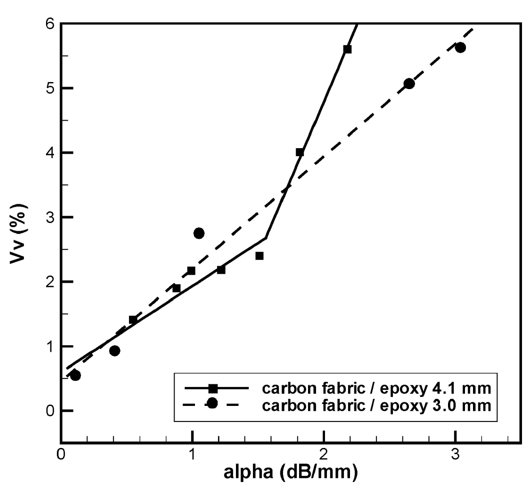

Fig. 1 Void content as a function of ultrasonic absorption coefficient α for carbon fabric/epoxy.

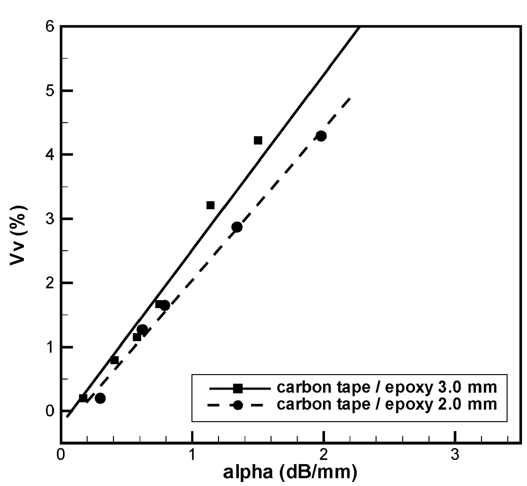

Fig. 2 Void content as a function of ultrasonic absorption coefficient α for carbon tape/epoxy laminates with different thicknesses.

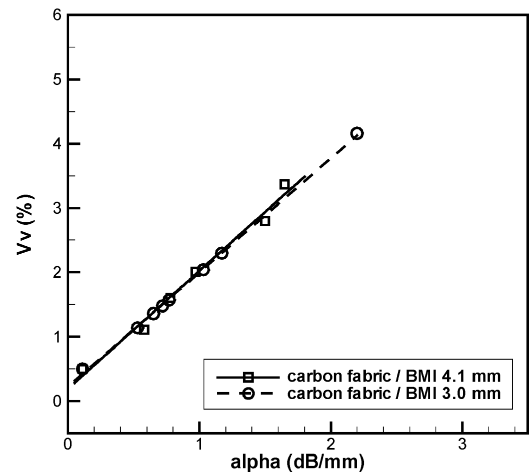

Fig. 3 Void content as a function of ultrasonic absorption coefficient α for carbon fabric/BMI laminates with different thicknesses.

Ultrasonic attenuation depends on a number of factors: laminate thickness, type of reinforcement, matrix material, fiber content, and the internal condition of the material, which includes the void content. Moreover, the shape, size, and distribution of voids in the laminate and parameters such as the ultrasound frequency, the size of the probe, and the calibration procedure also affect the absorption coefficient measurements. Therefore, it is difficult to compare the ultrasonic attenuation results obtained by other researchers without a full knowledge of all factors that affect the measurements.

The influence of the type of matrix, reinforcement, and the specimen thickness on the absorption coefficient can be discussed based on the experimental results presented in Figs. 1–3.

Given that the transmission loss A_t varies linearly with the thickness, the absorption coefficient is expected to be independent on the laminate thickness. However, previous results in the literature have demonstrated that a nonlinear relationship between void content and ultrasonic absorption coefficient may exist. A bilinear relationship was observed for carbon tape/epoxy laminates by Stone and Clarke[13] for 2.0-mm-thick specimens. Almeida and Nogueira Neto,[7] Costa et al.,[2] and Costa[3] also reported a similar behavior for these types of laminates. Figure 1 shows that the experimental results obtained for the thicker carbon fabric/epoxy laminates (4.1 mm) indicate the same type of trend over the tested range. Therefore, based on these previous results, a bi-linear relationship was assumed for this case, despite the small number of experimental points. Note in Fig. 1 that the thickness has little effect on the ultrasonic absorption up to 3% of void content. Above this void content value, there is a larger discrepancy between the results obtained for the 4.1-mm- and 3.0-mm-thick carbon fabric/epoxy specimens. The regions defined by the straight lines in Fig. 1 are functions of the size and shape of the voids. A transition region, representative of intermediate behavior due to the simultaneous presence of small and large pores, can also be observed in Fig. 1. The typical voids present in the carbon/epoxy laminate with high void content contribute to the second part of the curve of Fig. 1. These pores are probably originated by the coalescence of smaller pores present in the carbon/epoxy laminates.[2] According to Costa et al.,[2] the shape, size, and distribution of voids in the 4.1-mm-thick laminate change for high void contents, changing the value of the absorption coefficient.

On the other hand, Fig. 2 shows that, for carbon tape/epoxy specimens, there is a reasonable agreement between the absorption coefficient measurements for the 3.0-mm- and 2.0-mm-thick laminates. The laminate thickness does not affect the absorption coefficient for the carbon fabric/BMI laminates, as shown in Fig. 3.

When Figs. 1 and 3 are compared, it can be observed that the type of matrix has little influence on the absorption coefficient for carbon fabric reinforced laminates. The behavior of the epoxy and BMI matrix systems is very similar, except that the blinear relation is not observed for the BMI laminates within the considered range of void content.

The type of reinforcement may also affect the ultrasonic attenuation. Costa et al.[2] showed that the typical shape, size, and location of the voids depend on the type of reinforcement. When Figs. 1 and 2, are compared, it can be concluded that there is a significant discrepancy due to the type of reinforcement, particularly for low void contents.

Fracture Criterion

A fracture criterion that correlates fracture stress with void content or, alternatively, to ultrasonic attenuation, is needed to establish an acceptance level for the inspection. Criteria to predict the laminate strength under certain loading conditions in the presence of voids are scarce in the literature. Almeida and Nogueira Neto[7] proposed a fracture criterion that presented good correlation with experimental data on the bending strength of composite laminates with voids. The same idea was successfully applied to predict the interlaminar shear strength by Almeida and Santacreu,[6] Jeong,[5] Costa et al.,[2] and Costa.[3] Almeida and Nogueira Neto[7] also took advantage of the form of the equation to estimate the critical void content defined as the void content below which the strength of the laminate is not significantly affected by the presence of the voids. A similar approach was used by Soriano and Almeida[18] to analyze the fracture strength data of composite laminates with circular notches.

The considered fracture criterion for the strength of composite laminates containing voids is given by

$$\sigma_f = H(\alpha)^{-m} \tag{2}$$

where σ_f is the fracture stress, H is the laminate toughness, α is the ultrasonic absorption coefficient in decibels per millimeter, and m is the slope parameter.

Equation (2) provides a good fit to experimental results for specimens with voids,[2,3,5–7] however, it predicts infinite fracture stress for void-free laminates. To avoid this inconsistency, the fracture criterion assumes that, for low void content, fracture occurs according to classical fracture mechanisms with no influence of void content (fiber microbuckling for compression and shear failure for ILSS tests). Therefore, for low void content, the fracture stress σ_f is assumed to be given by

$$S_f = S_{f0} \tag{3}$$

where σ_{f0} is the laminate fracture stress for low void content.

Equating Eqs. (2) and (3) yields a critical value for the ultrasonic absorption coefficient α_{cr}, below which the void content does not affect the laminate strength. The value of α_{cr} can be computed from

$$\log(\alpha_{\mathrm{cr}}) = -(1/m)\log(\sigma_{f0}/H) \tag{4}$$

where σ_{f0} is the fracture stress of a laminated with low void content and α_{cr} is the critical value of the ultrasonic absorption coefficient. Note that the definition of the critical ultrasonic absorption coefficient provides a systematic approach to establish a maximum allowable value for the void content. The approach is derived from the mathematical form of the fracture criterion, which, in turn, is a consequence of the basic assumptions described earlier. Therefore, the critical ultrasonic absorption coefficient α_{cr} should be interpreted as a reference value for the minimum value of void content that affects the laminate strength, rather than as a physical characteristic of the laminate.

The proposed criterion in logarithmic form becomes

$$\log(\sigma_f) = \begin{cases} \log(\sigma_{f0}) & \text{if} \quad \alpha \le \alpha_{\mathrm{cr}} \\ \log(H) - m\log(\alpha) & \text{if} \quad \alpha > \alpha_{\mathrm{cr}} \end{cases} \tag{5}$$

Therefore, the criterion proposed by Almeida and Nogueira Neto[7] implies that the logarithmic plot of the fracture stress σ_f, as a function of the ultrasonic absorption coefficient α, should be approximately linear for $\alpha > \alpha_{\mathrm{cr}}$ and constant for $\alpha \le \alpha_{\mathrm{cr}}$. Logarithmic plots of the experimental results are presented to assess the validity of this hypothesis for all cases considered in the present work (Figs. 4–11). A straight line obtained from a best-fit procedure is included in all plots. Note that, to be consistent with Eq. (5), the best-fit procedure must not include the reference laminate that corresponds to the fracture stress of a laminated with low void content, σ_{f0}.

Figures 4–6 show the interlaminar shear strength results for carbon fabric and tape/epoxy and carbon fabric/BMI laminates. These results were obtained in a previous work[2] and are repeated here for completeness. Figures 7–9 show the results obtained in this work

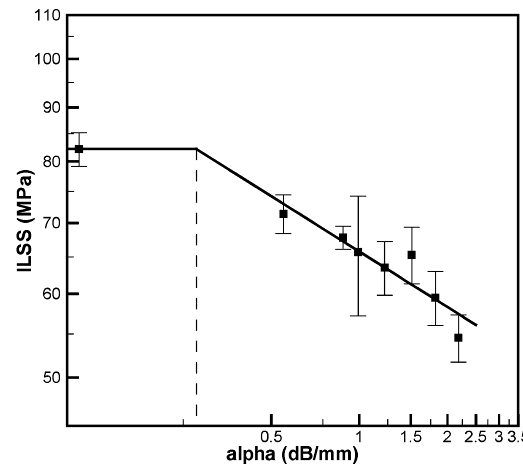

Fig. 4 Logarithmic plot of interlaminar shear strength as a function of ultrasonic absorption coefficient α for carbon fabric/epoxy laminates.

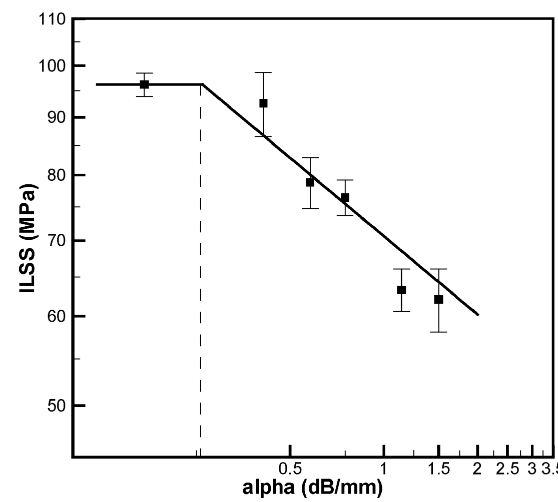

Fig. 5 Logarithmic plot of interlaminar shear strength as a function of ultrasonic absorption coefficient α for carbon tape/epoxy laminates.

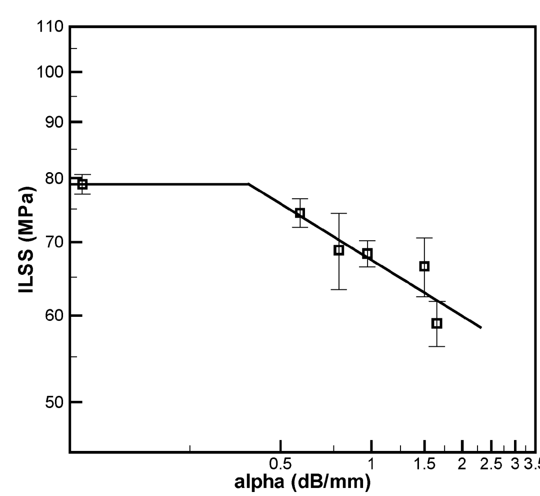

Fig. 6 Logarithmic plot of interlaminar shear strength as a function of ultrasonic absorption coefficient α for carbon fabric/BMI laminates.

Table 2 Fracture parameters for all laminates used in interlaminar shear and compressive strength tests

Laminate	m	H, MPa $(\text{dB/mm})^{-m}$	α_{critical}, dB/mm	V_{critical}, %
		ILSS		
Carbon fabric/epoxy	0.17	65.8	0.28	0.97
Carbon fabric/BMI	0.17	67.4	0.39	0.91
Carbon tape/epoxy	0.23	70.6	0.26	0.49
		Compressive strength		
Carbon fabric/epoxy	0.08	794	0.32	1.02
Carbon fabric/BMI	0.10	796	0.46	1.04
Carbon tape/epoxy	0.25	798	0.36	0.53

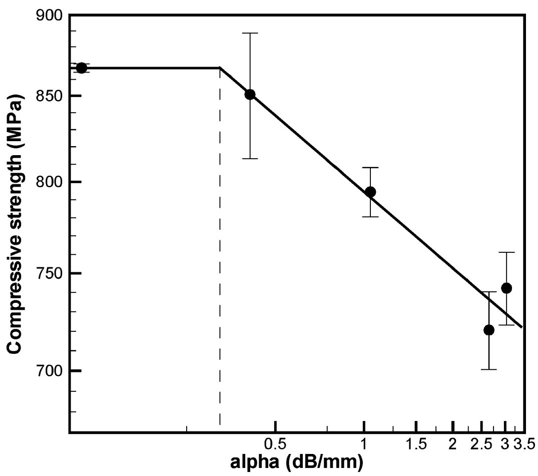

Fig. 7 Logarithmic plot of compressive strength as a function of ultrasonic absorption coefficient α for carbon fabric/epoxy laminates.

for the compressive strength of carbon fabric and tape/epoxy and carbon fabric/BMI laminates.

To verify the robustness of the fracture criterion, it was also applied to experimental data obtained independently. Figure 10 shows the application of the proposed fracture criterion to the results obtained by Stone and Clarke[13] for the interlaminar shear strength of carbon tape/epoxy laminates with voids. Similarly, the experimental results obtained by Suarez et al.[4] for the compressive strength of carbon/epoxy laminates with voids are presented in Fig. 11.

The results shown in Figs. 4–11 demonstrate that a good agreement with the experimental results was obtained from the application of the criterion proposed by Almeida and Nogueira Neto[7] to fit the fracture stress σ_f as a function of the absorption coefficient α for all cases considered. Note that the experimental data include the effect of load type (compression and interlaminar shear), type of matrix (epoxy and BMI), type of reinforcement (unidirectional tape and fabric), and experimental data from other researchers. Therefore, the proposed fracture criterion yields good estimates of the laminate fracture stress for a wide range of situations, provided that adequate values for the fracture parameters are used in each case. The fracture parameters are the laminate toughness H, the slope parameter m, and the critical void content, either in terms of the absorption coefficient α_{cr} (decibels per millimeter), or in terms of volume fraction V_{cr} (percent).

The values of the fracture parameters are obtained from the linear regression procedure based on Eq. (5). The resulting values for all cases investigated are listed in Table 2.

The slope parameter m depends on the reinforcement and loading type. The value of m is about 0.24 either under compressive or interlaminar shear loading for carbon tape/epoxy laminates. However, for carbon fabric reinforced laminates, the value of m strongly depends on the loading type, but it is nearly independent on the resin system. For compressive strength, $m = 0.17$ for both the epoxy and BMI specimens; for the ILSS results, $m = 0.08$ and 0.10 for epoxy and BMI matrices, respectively.

The laminate toughness H depends primarily on the loading type. The effect of the type of reinforcement and resin system is small, as

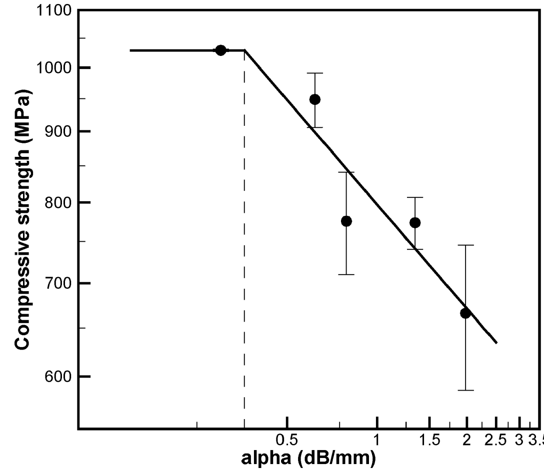

Fig. 8 Logarithmic plot of compressive strength as a function of ultrasonic absorption coefficient α for carbon tape/epoxy laminates.

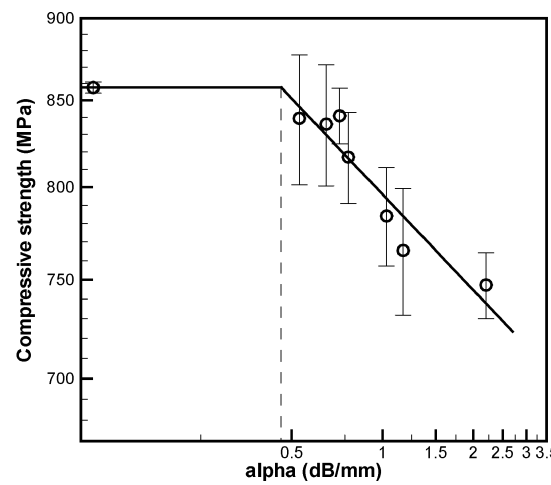

Fig. 9 Logarithmic plot of compressive strength as a function of ultrasonic absorption coefficient α for carbon fabric/BMI laminates.

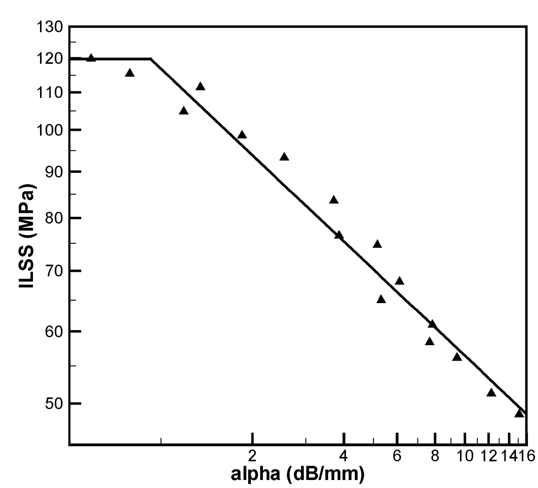

Fig. 10 Logarithmic plot of interlaminar shear strength as a function of ultrasonic absorption coefficient α for carbon tape/epoxy laminates by Stone and Clarke.[13]

demonstrated by the results in Table 2. The epoxy and BMI matrices have very similar laminate toughness.

An important fracture parameter is the critical void content, which establishes an acceptance criterion for the nondestructive inspection of composite laminates. When expressed in terms of the critical absorption coefficient α_{cr}, it depends on the resin system, type of reinforcement, and loading. For carbon/epoxy laminates under ILSS loading, the critical absorption coefficient is 0.26 dB/mm for

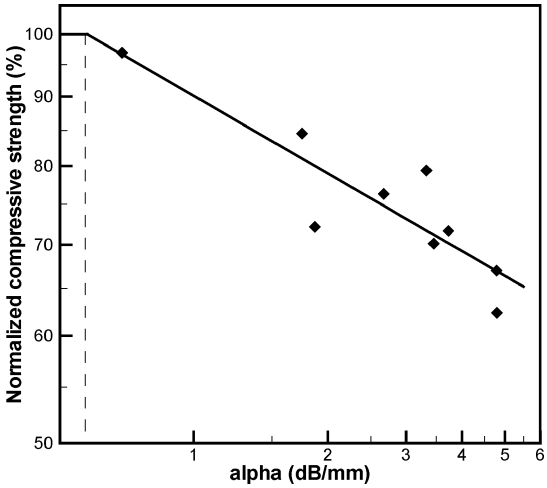

Fig. 11 Logarithmic plot of compressive strength as a function of ultrasonic absorption coefficient α for carbon tape/epoxy laminates by Suarez et al.[4]

tape and 0.28 dB/mm for fabric reinforcement; for compressive strength measurements, the critical absorption coefficient is 0.32 and 0.36 dB/mm for fabric and tape reinforcements, respectively. These results indicate that the type of reinforcement has little influence on the critical absorption coefficient, whereas the type of loading has a significant effect. The influence of the matrix material may be assessed by comparing the results for carbon fabric/epoxy and carbon fabric/BMI specimens. The critical absorption coefficient is higher for the BMI specimens; therefore, this resin system may be regarded as more tolerant to defects than the tested epoxy system.

When the critical void content is expressed in terms of critical volume fraction V_{cr}, the dependence on the studied parameters is quite different. V_{cr} varies from 0.91 to 1.04% for all specimens with fabric reinforcement, whereas the tape reinforced laminates have V_{cr} from 0.49 to 0.53%. Therefore, in terms of volume fraction, the critical void content depends mostly on the type of reinforcement, with little influence from the load type and matrix system. Note, however, that from the point of view of nondestructive inspection, the critical void content must be established in terms of the parameters of ultrasonic inspection, that is, the critical absorption coefficient α_{cr}.

Conclusions

An experimental program aiming at establishing acceptance levels for the attenuation level in the ultrasonic inspection of composite laminates is described. Laminates produced with carbon fabric/epoxy, carbon tape/epoxy, and carbon fabric/BMI were produced with intentionally high void content. The absorption coefficient was measured for all specimens and shown to vary approximately linearly with the void content, with the exception of the carbon fabric/epoxy laminates that presented a blinear relationship with void content, corroborating previous results.

A fracture criterion proposed by Almeida and Nogueira Neto[7] was applied to the experimental data to correlate the interlaminar shear strength and compressive strength of the laminates to the absorption coefficient. The theory presented good correlation with the experimental data for all cases, including experimental data independently obtained by other researchers. Therefore, it was demonstrated to be a useful nondestructive inspection aid in certifying the structural integrity and safety of composites laminates containing porosity.

The application of the fracture criterion to the experimental data establishes a systematic approach to estimating an inspection acceptance criterion based on a critical void content below which the strength of the laminate is not significantly affected by the presence of the voids. The critical void content may be described either in terms of the absorption coefficient in the ultrasonic inspection or in terms of the volume fraction. It is shown that, when expressed in terms of the critical absorption coefficient, the critical void content depends on the resin system, type of reinforcement, and loading. However, the resulting values are also dependent on parameters of the ultrasonic inspection, namely, the frequency, diameter of the probe, calibration procedure, etc. Therefore, the estimated critical absorption coefficient may only be used as an inspection criterion for the same conditions used in this work. The critical void content in terms of volume fraction depends mostly on the type of reinforcement. These data, however, cannot be directly used as an acceptance criterion in a non-destructive inspection of composite laminates.

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B. Sankar
Associate Editor