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NON-DESTRUCTIVE EVALUATION OF POROSITY AND ITS EFFECT ON MECHANICAL PROPERTIES OF CARBON FIBER REINFORCED POLYMER COMPOSITE MATERIALS

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ABSTRACT. In this work, an attempt is made to induce porosity of varied levels in carbon fiber reinforced epoxy based polymer composite laminates fabricated using preregs by varying the fabrication parameters such as applied vacuum, autoclave pressure and curing temperature. Different NDE tools have been utilized to evaluate the porosity content and correlate with measurable parameters of different NDE techniques. Primarily, ultrasonic imaging and real time digital X-ray imaging have been tried to obtain a measurable parameter which can represent or reflect the amount of porosity contained in the composite laminate. Also, effect of varied porosity content on mechanical properties of the CFRP composite materials is investigated through a series of experimental investigations. The outcome of the experimental approach has yielded interesting and encouraging trend as a first step towards developing an NDE tool for quantification of effect of varied porosity in the polymer composite materials.

KEYWORDS: NDE, Ultrasonics, Porosity, CFRP Composites

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INTRODUCTION

Porosity invariably gets introduced in polymer matrix composite materials during the fabrication process. While it is a fact that porosity can not be totally avoided in this type of material, the presence of such defects beyond a certain limit can be highly detrimental to the mechanical properties of the final product and hence their performance as a structural component. Though there are standard destructive methods in practice to quantify the porosity, the need for a Non-destructive Evaluation (NDE) tool to evaluate polymer composite component for the porosity content can not be over emphasized.

Porosity is usually determined as the distribution of microscopic interfacial microvoids located in the matrix between plies of fibers and scattered over the volume of the composite laminate. Non-destructive evaluation of Porosity is an area particularly of great interest in aerospace industry due to increasing usage of polymer composite materials for primary and secondary structural components. Literature survey indicates that there is no established non-destructive evaluation technique to quantify porosity in composite parts.

Voids and porosity form in composite laminates primarily because of air bubbles and volatile substances liberated during curing. In addition, void formation is due to the chemical composition, method of mixing the binder and preparation of the prepreg, mechanical treatment, configuration and thickness of the composite laminate, number of gates used, method of creating the molding pressure, moisture content, etc. In many cases, insufficient

pressure during curing is the most important factor that affects formation of porosity in a composite laminate. The porosity of the finished products is thus the consequence of many factors which are difficult to control.

Porosity above a critical level affects static and fatigue strength of composite parts and a greater susceptibility to water penetration and environmental effects. During subsequent loading, these voids act as nuclei of further damage growth resulting in strength degradation. Lowest possible porosity levels are thus essential for ensuring the performance of fiber-reinforced composite structures.

Though there have been attempts to study the effect of porosity on NDE measurements and on mechanical properties degradation they have been sparsely spread. Also, they have been to either qualitatively assess the porosity content through NDE or to study the effect of porosity on some mechanical property degradation. Thus, a concerted effort to correlate an effective NDE parameter, to correlate the effect of porosity content on different mechanical properties and to arrive at quantitative correlation between them is still a tough challenge.

Sergio Frascino Muller de Almeida and Zabulon dos Santos Norueira Neto [1] carried out an experimental program to assess the effect of void content on static strength and fatigue life of composite laminates under flexural loading. The fatigue test results and the proposed theory indicated that voids have a strong detrimental effect on composite structures. M. Daniel, S. C. Wooh and Komsky [2] discussed two methods for determination of material attenuation; direct or absolute methods for materials with low signal loss and indirect or relative methods for materials with higher signal loss. S.M. Handley and co-authors [3] used polar backscatter and frequency dependent attenuation methods to characterize porosity. Mark P. Connolly [4] has described an infrared thermographic technique, which can be used to determine the degree of porosity in polymeric matrix composite materials.

In the present work an attempt is made to induce porosity of varied levels in carbon fiber reinforced epoxy based polymer composite laminates, to detect them and correlate with parameters of different NDE techniques. Primarily, non-contact water immersion Ultrasonic C-scan imaging has been adopted for the experimental investigations and Real time digital X-ray imaging also has been tried to obtain a measurable parameter which can represent or reflect the amount of porosity contained in the composite laminate.

EXPERIMENTAL DETAILS

Inducing Porosity in the Laminates

The most challenging task here is to induce different levels of porosity in the laminates. Also the distribution of pores throughout the laminate has to be uniform and consistent. Varying curing pressure is one way of inducing varied porosity in the laminates. The laminates fabricated using less pressure are expected to induce more porosity as air bubbles and volatile substances liberated during curing will not be squeezed out completely. Also, the distribution of pores is expected to be uniform, as the pressure is uniform throughout the laminate. Different curing pressures within the available range can be used to achieve varied porosity levels in the laminates.

Most of the aircraft composite components are fabricated using autoclave technology. Components are made with prepregs and curing pressures are up to 7 bars pressure which helps in maintaining consistent fiber-volume fraction and with very low porosity levels because of very high curing pressure. Wide range of curing pressures available from 1 bar to 7 bars allows fabricating test specimens with equally wide range of porosity levels.

Consistent laminates with uniformly distributed pores can be fabricated with this method. The idea of using glass micro spheres during lay-up in between layers is found in literature. But this method has the limitations in achieving the controlled porosity content with consistency and uniform distribution. Further, the glass balloons may not respond in the same way as the pores when nondestructively analyzed. Thus, the method chosen here to fabricate the laminates with varied porosity is varying the autoclave pressure and applied vacuum.

MATERIALS AND SAMPLES

Fabrication of CFRP Prepreg Laminates

To achieve different levels of porosity in the CFRP laminates fabricated from carbon epoxy based prepregs, different combinations of fabrication and autoclave curing parameters were tried. Sets of 10, 20 and 40 layered, symmetric and balanced lay-up sequence with a quasi-isotropic configuration were fabricated. In each set one healthy laminate is required with porosity percentage as low as possible. This laminate was fabricated by following the autoclave curing procedure prescribed by the prepreg manufacturer, at full vacuum (700mm of Hg) and 7 bar external pressure and curing in an autoclave at an elevated temperature of 125 °C. This laminate is used as a reference. To obtain varied porosity levels in different sets of laminates following sets of curing cycle parameters were utilized.

Healthy Laminates : 7 bar External Pressure and Full Vacuum
 Porous Laminate 1 : 7 bar External Pressure and No Vacuum
 Porous Laminate 2 : 3.5 bar External Pressure and No Vacuum
 Porous Laminate 3 : No External Pressure and Full Vacuum

Burn Out Tests to Determine the Induced Porosity in CFRP Laminates

Burn out test was performed according to ASTM D 2734 standard to determine void content in fiber reinforced composites. Six samples each from the laminates were cut out and tests carried out as per the standard procedure. The average porosity content for these laminates is as presented in Table 1.

Table 1. Induced Porosity content for different sets of CFRP laminates fabricated

Sl. No.	Type of laminate	%Porosity in 10 layered laminates	%Porosity in 20 layered laminates	%Porosity in 40 layered laminates
1	Healthy	3.1405	4.5886	1.603
2	Porous 1	3.2180	4.7849	2.456
3	Porous 2	4.3704	5.3846	5.431
4	Porous 3	5.1574	6.7999	8.660

NON-DESTRUCTIVE EVALUATION (NDE) OF INDUCED POROSITY

Non contact water immersion ultrasonic scanning and real time digital radiographic imaging techniques were utilized to evaluate the fabricated sets of CFRP laminates for porosity content.

Ultrasonic Imaging

The CFRP laminates were subjected to ultrasonic scanning using sets of focused probes of frequency 1, 2 and 5MHz. Different test parameters were tried in terms of area, resolution, input pulse energy, receiver amplifier gain etc., and the probes were carefully aligned in line with each other and normal to the plane of test specimen. Each probe is placed at a distance equal to the focal length from the surface of the laminate. Once optimized, these parameters were maintained unaltered for all the laminates. Sample images of the set of laminates with different porosity levels under identical test parameters using 5 MHz probe with three inch focal length in water are shown in Fig.1. The different colors seen in each of these images represent different ranges of the received signal amplitude values. While white color represents maximum within the area scanned, blue indicates zero output signal level and the other colors represent different ranges of amplitude values in between as indicated by the color coded bar displayed to the left of the image.

As can be observed from these images corresponding to different values of porosity there is a definite trend showing decrease in received signal level with increase in porosity. Just to verify the effect of scan parameters such as resolution and speed of scan on the outcome, scanning was performed at higher resolution (0.025 mm steps) which takes much longer time compared to coarser scanning steps of 0.5 mm. It can be seen from (Fig.2a) the results that even a faster scan of larger area with coarser resolution yielded similar results to finer scan images. Figure.2b shows the variation in receiver signal amplitude with varied porosity for different frequency probes. As expected, though there is higher attenuation at higher ultrasonic frequency, the variation with porosity content show similar trends at different frequencies.

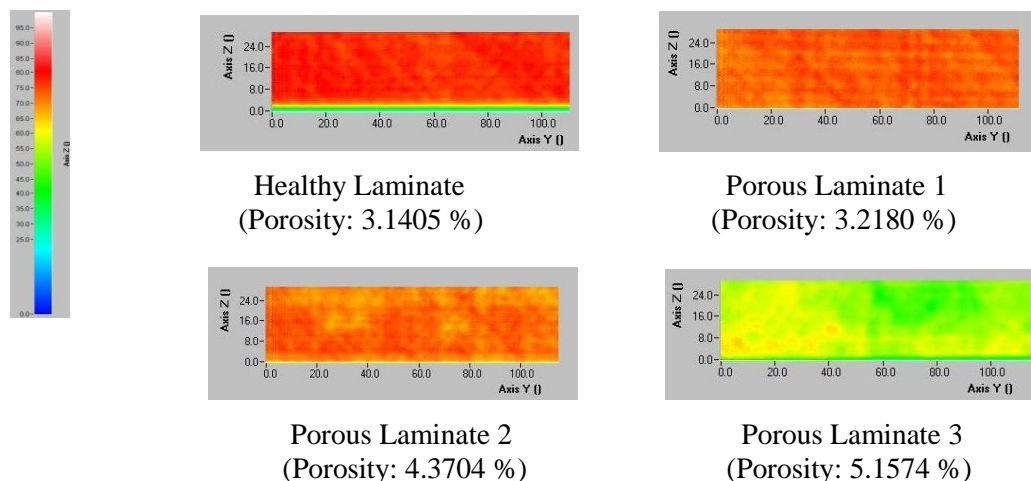


FIGURE 1. C-Scan images of laminates with different porosity levels

REAL-TIME DIGITAL RADIOGRAPHY

Real time digital X-ray imaging was performed on the sets of CFRP laminates to look for variation in the transmitted radiation with respect to varied porosity. The experimental setup consisted of a portable 100 kV source and portable amorphous silicon based Flat panel X-ray detector.

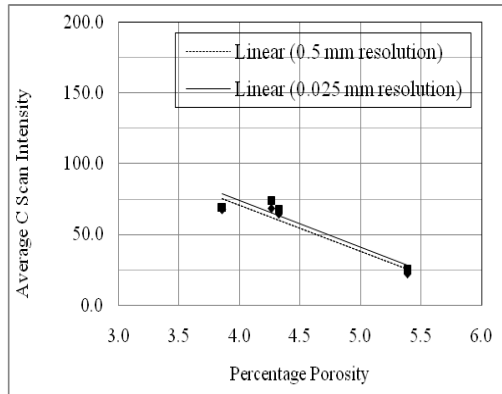
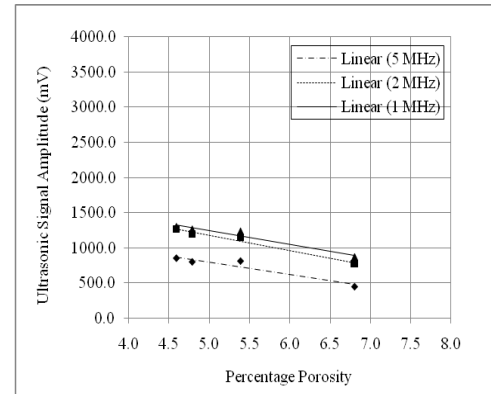


FIGURE. 2(a) C-scan results with coarse and fine resolution



(b) Frequency dependence of signal attenuation

Different test variables and combinations were tried by trial error method before arriving at a set of parameters, optimum source kV and radiation exposure in milliamp-sec. Sets of images obtained for CFRP laminates were processed to obtain average pixel intensity for each of the laminates with different porosity levels. Though quantitatively not very discriminating, the average intensity values do show a trend with increasing porosity. This technique may not be the best quantitative measure as the laminates themselves are thin structures of lower density materials which may not significantly represent the change in porosity content that can appear as density variation on the obtained image. Fig.3. shows a sample plot of variation in average pixel intensity with porosity in these CFRP laminates.

MECHANICAL PROPERTY EVALUATION

To study the effect of varied porosity on the mechanical properties of the CFRP laminates, standard open – hole compression tests and Inter Laminar Shear Strength (ILSS) tests were performed on coupons cut out from the sets of laminates with varied porosity content. Standard ASTM methods were adopted for both these sets of tests.

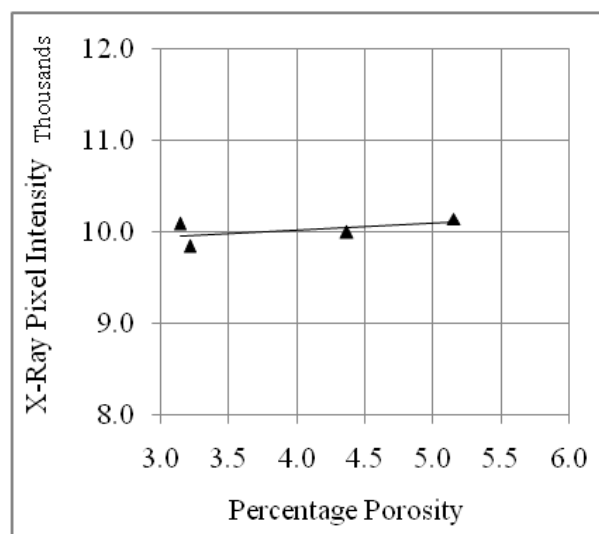


FIGURE.3. X-ray image intensity variation with porosity in CFRP laminates

Open Hole Compression Test

The tests were carried out to determine the open-hole compressive strength of carbon fibre reinforced composite laminates. The ASTM D 6484 was followed. The test samples were rectangular strips of length 300 mm and width 36 mm with a 6.0 mm drilled hole at the center. The test specimen is face-supported in a multi-piece bolted support fixture shown in Fig.4. In this test procedure, the fixture is hydraulically gripped on each end and the compressive force is transmitted by means of friction through the fixture and into the test specimen. The fixtures also allow a slight clearance between the fixture and the gage section of the specimen, in order to minimize grip failures and friction effects. The portion of the force initially transferred into the support fixture is transmitted by shear into the test specimen. The only acceptable failure mode for ultimate open-hole compressive strength is one which passes through the hole in the test specimen. Ultimate strength is calculated based on the gross cross-sectional area, disregarding the presence of the hole. The results of these tests are plotted and presented in Fig.5. The open hole compression strength of the CFRP laminates show a decreasing trend with increase in porosity content.

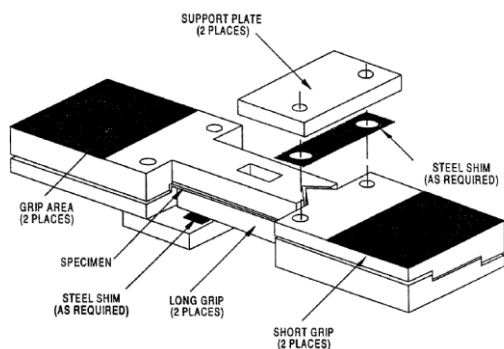


FIGURE. 4. Open Hole Compression Test Fixture Assembly

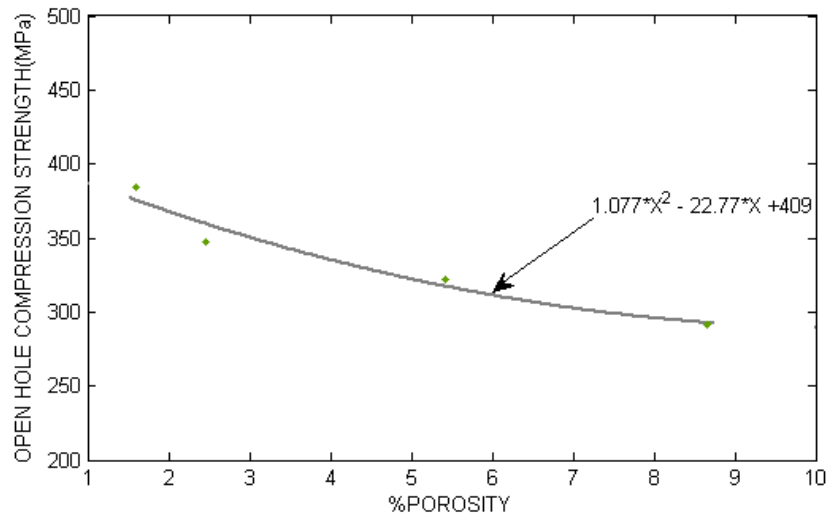


FIGURE .5. Open hole compression strength variation with porosity

Interlaminar Shear Strength Test

Another important mechanical property for polymer based multilayered composites is the Inter-laminar Shear Strength which is the maximum shear stress that exists between the layers of the laminate. This test is carried out with reference to ASTM standard D2344. Figure.6 below shows the experimental set up for the ILSS tests in three point bend configuration. The size of samples in terms of physical dimensions are very small in these tests. Coupons cut out from sets of CFRP laminates with different porosity contents were subjected to the ILSS tests and the results obtained are plotted as shown in Fig.6b. The effect of porosity content on the ILSS of the CFRP laminates has been observed to be very significant. There appears to be drastic drop in this property as the porosity content goes beyond 2%.

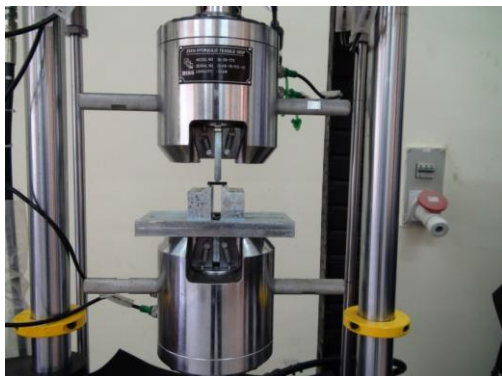
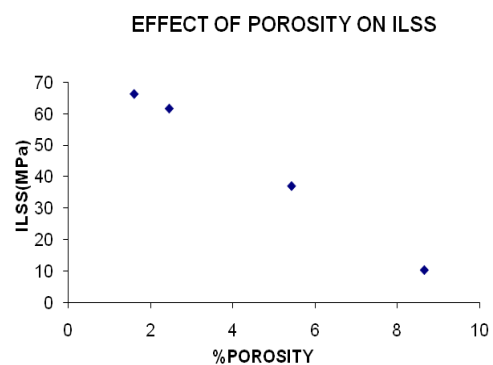


FIGURE 6(a). ILSS experimental set up



(b) Variation in ILSS with porosity

CONCLUSION

The experimental investigations undertaken to study the effect of porosity content on the mechanical property degradation in CFRP laminates have yielded interesting and encouraging results. The NDE approaches tried show that ultrasonic based techniques can be very effective for such applications. The results also show that the faster scans obtained using lesser resolution can still give good enough results that reflect on the variations in the porosity content in the material. On the other hand even the high resolution digital radiographic imaging may not be as effective in determining the variation in porosity in these laminates. This could be due to the fact that the composites are generally thin structures of low density materials and the effect of small variation in porosity may not change the X-ray absorption significantly.

The mechanical property evaluation through standard destructive tests shows that while the effect of porosity on ILSS is very significant and drastic, the same may not be true when it comes other property the in-plane compressive strength as found by the open hole compression tests. Further tests along the similar line with larger number of samples will help in obtaining appropriate quantitative correlation between ultrasonic NDE parameter and the degradation due to porosity variation in such materials.

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