Effect of Defects Part II: Multiscale Effect of Microvoids, Orientation of Rivet Holes on the Damage Propagation, and Ultimate Failure Strength of Composites

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Abstract: Material properties at the vicinity of the cut-outs in composites are not entirely defect-free. The interaction of multiple cutouts like rivet holes, the repercussion of their configuration on crack propagation, and ultimate strength were predicted using Peridynamic method and the results are reported in this article. The effect of microscale defects at the vicinity of the cutouts on macroscale damage propagation were shown to have quantifiable manifestation. This study focused on two to four holes in unidirectional composite plates with 0°, 45°, and 90° fiber directions, while the vicinity of a hole was considered degraded. Numerical results were validated using quantitative ultrasonic image correlation (QUIC) and the tensile test. Both the experimental and numerical results confirmed that the strength of the horizontal configuration is higher than the vertical in the plates with two holes. Furthermore, the square configuration was found to be stronger than the diamond configuration with four holes. When the effect of microscale defects was considered, the prediction of ultimate strength was better compared to the experimental results. The predictive model could be reliably used for progressive damage analysis.

Keywords: composite failure; progressive damage analysis; multiple holes; open hole testing strength; damage propagation interaction; peridynamics

1. Introduction

Fiber-reinforced composites are extensively used in different industries such as aerospace, construction, vehicle, etc. [1]. One of the most common methods to manufacture or assemble composite structures is to fasten two composite structural parts [2]. Fastening composite structures can be performed by pin joints, bolt-filled holes, thread joints, clamped joints, etc. [3]. In this procedure, the creation of holes with different configurations is required. Holes in the composite structures may create zones with a high-stress concentration around the edge of the holes [4,5]. Damage may nucleate because of high-stress concentration around the holes. The damage may start to propagate because of the fiber breakage, matrix cracking, fiber-matrix splitting, and shear-out failure when the composite structures are subjected to static or dynamic loads [6]. Consequently, it reduces the strength of the load-bearing composite structural parts and final failure happens earlier than expected. It was found that, unlike isotropic material, damage nucleation, damage path, damage propagation, and the ultimate strength of the composite structures with holes are not only dependent on the material properties, but also depend on the fiber orientation, hole locations, number of holes along the load line, and the orientations of the holes with respect to the fiber direction [7].

Additionally, creating local discontinuity on composite plates may create microvoids or fiber breakage around the holes. Moreover, manufacturing defects are inevitable in all kinds of composite materials due to resin transfer molding (RTM) or chemical vapor
infiltration (CVI) processes [8]. One of the most common manufacturing defects that occurs in composite materials is microvoids. The material properties are degraded around the holes because of microvoids. The amount of degradation of material properties should be considered to accurately obtain the strength of composite materials with holes. Thus, the progressive failure analysis of open-hole composites has been a topic of interest for decades. Here, we reviewed different methods of progressive failure methods, the Peridynamic method, and considered degraded material properties to obtain the strength of the composite materials analyzed.

The researchers attempted to predict the final failure and strength of open-hole composite structures with stress concentrations. The point/average stress model is one of the primary methods for obtaining the strength of an anisotropic plate [9]. In this method, failure is predicted to occur once the stress at a certain distance or average stress over a certain distance from the notch tip reaches the strength of the plate without a notch. Another method is followed by linear elastic fracture mechanics. In this method, failure is predicted to occur if the notch is introduced by an equivalent crack that attains the critical size [10]. These methods can predict the strength of composite structures reasonably. However, these models are heavily parameter dependent, are unknown, and can only be found through extensive experiments. Niesłony and Böhm [11] determined the crack initiation for isotropic materials using the Finite Element (FE) method and stress-strain curve for the part of a machine with four holes.

Progressive damage may cause stress redistribution [12]. To consider stress redistribution, a progressive failure analysis of composite structures was introduced to predict the strength of composite structures with a hole. The material degradation method (MDM) and continuum damage mechanics (CMD) approach were used to model in-plane damage modes such as fiber failure and matrix cracks [13]. Riccio and et al. modeled damage propagation in the composite plate with a single hole and embedded delamination under a compressive load using the finite element method and fracture mechanics [14]. Hufner and Accorsi [15] applied the progressive failure model to woven composites with one hole. The results were validated by the digital image correlation (DIC) method. They employed the stiffness reduction technique after the failure. This approach was implemented in ABAQUS software using a user material subroutine. CMD and MDM are suffering from a lack of a strong physical basis to quantify the percentage of material degradation accurately. Researchers have used the discrete ply model approach to predict the final failure of open-hole composite materials [16–18]. However, this method is computationally expensive.

The cohesive zone model (CZM) is another method that can be used for the progressive damage model. Zou developed a model to predict the damage propagation and strength of connected laminated structures with a single bolt [19]. Rozylko studied the failure of the thin-walled composite structure made by Carbon Fiber Reinforced Plastic (CFRP) using progressive failure analysis and CZM. They also validated the results experimentally [20,21]. Ridha et al. [22] modeled the progressive failure in notched composite laminates with different stacking sequences. The max stress and Tsai–Wu failure criterion were used to model in-plane damages. The CZM was employed to model the interfacial behavior. CZM was used to employ the composite failure analysis using the standard finite element method and can be categorized into two categories: (a) the continuum model [23] and (b) the cohesive interface element [24,25] model. The continuum model is independent of mesh generation. However, this is not suitable for the propagation of the dominant crack. The cohesive interface element can model matrix cracks and delamination interfaces. However, cohesive elements should be aligned with the finite element, which may cause difficulty in meshing for complex geometry.

To overcome this limitation in the standard finite element method, the extended finite element method (XFEM) was introduced [26,27]. Higuchi et al. [28] predicted the progressive damage and resultant failure of carbon fiber plastic laminates using a mesoscale simulation methodology. The evolution of the delamination and matrix cracking was performed using CZM. The CZM for delamination was performed using the interface element
and XFEM was employed for modeling matrix cracking. To overcome the limitation of the continuum damage model, Dongen et al. [29] introduced a method for progressive damage analysis of composite structures with one open-hole. The proposed methodology combined the continuum damage model and the cohesive zone model. Matrix crack and delamination criteria were used to simulate progressive damage using XFEM in ABAQUS software. However, using XFEM in ABAQUS software has some limitations including capturing one crack per side, per ply.

In the above methods, the fundamental partial differential equations (PDEs) are used to define the damage in a continuous body. It is hard to capture damage propagation using these methods due to intrinsic limitations. The main limitation is that the spatial derivatives are not defined at the crack tips as a singular point. Thus, these methods have similar trouble once the crack nucleates in a body. To overcome the limitation, a nonlocal theory was introduced by Silling [30] such that the spatial derivatives were not required for defining the fracture. This method is called the bond-based Peridynamic (PD) theory. Later, Silling et al. [31] generalized the bond-based PD theory into the state-based PD theory by considering the interaction of the number of material points located at a certain distance from each other. In comparison to classical continuum mechanics, PD theory employs the integral form of the equations of motion. By using the integral form of the equations of motion, crack initiation and propagation are captured at multiple sites without resorting to special crack-growth criteria. A large body of research was conducted on crack propagation on a unidirectional lamina with a center notch and the laminated composite with large-notch under the tensile load [32,33]. Tastan et al. [34] studied crack propagation in thin orthotropic flat plates under bending loads. They reported that the results are consistent with those obtained with classical computational methods. Additionally, they modeled the crack patterns in the orthotropic plates accurately. The damage progression in a laminated composite plate with a notch and open hole were studied by Yi-Le et al. [35]. In this study, the damage propagation and failure modes were found under a tensile load. Colavito et al. [36] analyzed the residual strength of composite laminates with a hole. The results showed that the PD results are in good agreement with the experimental results. A new bond-based Peridynamic modeling for composite laminates was introduced by Hu and Madenci [37]. The proposed method did not have any restriction on fiber orientation and material properties. Later, damage initiation and growth in a laminated composite with one hole was studied by Hu and Madenci [38]. The results were validated at the Air Force Research Laboratory (AFRL) for three different layups under fatigue loading to confirm the predicted pattern of damage progression and ultimate strength.

Huang and Talerja [39] presented the effect of a microvoid with the cylindrical and elliptical cross-sectional area on the elastic properties of unidirectional (UD) fiber-reinforced composite. The results showed that the void content contributed to degrading the out-of-plane modulus significantly, while the in-plane properties got less affected. Hyde et al. [40] studied the effect of microvoids on the strength of unidirectional (UD) fiber-reinforcement composite materials using the micromechanics-based finite element method. They considered two different void models, which were distributed spherical void shapes and a single inter-fiber void with triangle, circular, square, and pentagonal shapes. They found that the pentagonal inter-fiber decreased the strength of composite materials more than other void shapes. Tavaf et al. [41,42] developed a framework to quantify the degraded material properties for the carbon/carbon unidirectional composite materials due to manufacturing defects such as microvoids and fiber breakage. They considered the RVEs with multiple fibers and used the finite element method to calculate the effective material properties (EMPs). The results showed that all the EMPs degraded, even at the lower void percentage. Moreover, all the EMPs did not degrade with the same amount. Gao and et al. [43] calculated the elastic properties of braided composites with void defects. They also predicted the strength of the braided composite with the Mori–Tanaka method. Chao and et al. [44] studied the effect of porosity on flexural properties of 2D carbon/carbon composites. The results showed that the increase of porosity may accelerate the damage in 90 plies and
the severe delamination will thus be slightly aggravated. Qui and et al. [45] calculated the transverse mechanical properties of UD composites with irregular pores. They found that the effective transverse elastic properties decreased once the porosity and the pores of clustering increased.

According to the established literature, there are several methods to predict the strength of composite structures with an open-hole such as the material degradation method [13,15], cohesive zone model [19,23,46], extended finite element method [14,26–29], and experimental study [47–49]. Nevertheless, these methods have their own shortcomings which were already discussed. To avoid the inherent limitation of the approaches, the researchers used the Peridynamic method to analyze the progressive damage and predict the strength of composite structures with an open-hole [35]. However, in some composite structures which are used in aircrafts, multiple holes may exist. Thus, it is required to study the effect of multiple holes on the strength of composite structures. Recently, through both numerical and experimental studies, the strength of carbon/epoxy laminates with two holes in specific orientations was predicted [7]. However, the strength of composite structures with more than two holes, which are frequently used in aircraft structures, was not addressed. Additionally, to the best of the authors’ knowledge, the effect of degraded material properties on strength of unidirectional composite materials has not been studied. Thus, according to the existing literature, the effect of the degraded material properties, number of holes, and configurations on the strength of the composite structures with different fiber orientations is of utmost interest and the necessarily substantial way forward for the progressive damage analysis of composites.

In this study, the strength prediction was performed for unidirectional composite plates with different hole configurations and fiber orientations using a numerical and experimental technique. Next, the material properties around the hole were updated by considering the effect of microvoids on their engineering materials. The Peridynamic method was employed to study the effect of the interaction between holes positioned on the strength and crack growth in the unidirectional composite structure. The unidirectional composite plates were considered with one, two, and four holes, and different orientations under the rate of change of displacement. For each case, three fiber orientations, which are 0°, 45, and 90°, were considered. To validate the PD results and obtain the strength of the plates, tensile tests were performed. Further, the crack path was validated for each case using the scanning acoustic microscope (SAM) equipped with quantitative ultrasonic image correlation (QUIC) software. Finally, the strength of the UD composite was predicted using degraded EMPs around the hole. This paper is organized in the following sequence. First, the Peridynamic formulation in a unidirectional composite is explained. Next, the unidirectional composite with one, two, and four open holes were simulated under the rate of change of displacement, and the numerical results are discussed and compared with the experimental results. The summary of this study is explained in the conclusion section.

2. Peridynamic Theory and Numerical Simulations

The Peridynamic method is a nonlocal theory based on the interaction of a material point with other material points within a certain distance. This certain distance $H$ is called the “horizon” of material point $X$, introduced by radius $\delta$. All the material points ($\hat{X}$) placed within the horizon are called “family members” of $X$. In Figure 1, $X$ and $Y$ are the undeformed and deformed configuration of material points, respectively. For a bond-based theory, the interaction forces between the material point $X$ and its family member $X'$ are defined by a pair force $f$, and are in the opposite direction with identical magnitude. The integral form of the equations of motion is used in the PD theory compared to its differential representation. This result in the equations of motion is valid in the entire domain, even in presence of discontinuity, since the calculation of derivatives of displacement is not required. The equations of motion of the PD theory are expressed in Equation (1).

$$
\rho(x)\ddot{u}(X,t) = \int_H f(\eta,\xi) \, dV_{X'} + b(X,t) \quad \forall x \in \mathbb{R},
$$

(1)
where \( \rho \) is the material density at \( x \), \( u \) and \( \bar{u} \) are the displacements of material point \( X \) and \( X' \) at time \( t \), respectively, the volume of the material point is expressed by \( dV_{X} \), and \( b(X, t) \) is the body force. As shown in Figure 1, the pairwise force is considered between the material point \( X \) and \( X' \), which is dependent on the relative position at the undeformed state (\( \zeta \)) and deformed state (\( \eta \)) at time \( t \). The relative positions at the undeformed and the deformed state are given as

\[
\zeta = X - X', \quad \eta = \bar{u}'(X', t) - \bar{u}(X, t).
\] (2)

According to the bond-based PD theory, \( \mu \) is a parameter showing the status of a bond (intact or broken). The parameter \( c \) indicates the bond constant, and \( s \) is the bond stretch, which is expressed as

\[
s(\eta, \zeta) = \frac{||\eta + \zeta|| - ||\zeta||}{||\zeta||}. \tag{4}
\]

As indicated in Equations (2) and (3), \( ||\zeta|| \) is the bond length at the undeformed state and \( ||\eta + \zeta|| \) is the bond length after deformation. When the stretch between the material points violates the critical stretch, the bond is broken. The critical stretch is given by

\[
s_0 = \sqrt{\frac{10G_0}{\pi c \delta^3}} \tag{5}
\]

where \( G_0 \) is the energy release rate of the material point. The bond status parameter is defined as

\[
\mu(t, \eta, \zeta) = \begin{cases} 
1 & \text{if } s(t', \eta, \zeta) < s_0 \text{ for all } 0 \leq t' \leq t \\
0 & \text{otherwise}
\end{cases} \tag{6}
\]

The damage index at the material point \( x \) can be defined as

\[
\psi(X, t) = 1 - \frac{\int_H \mu(t, \eta, \zeta) dV_{X'}}{\int_H dV_{X'}}. \tag{7}
\]
Numerical solutions are required to solve Equation (1) using the PD method. To calculate the integral term of the internal force, the composite structure should be discretized with the number of material points. Thus, the integral term in Equation (1) is replaced with a finite sum. The equations of motion can be rewritten as [30]

\[
\rho \ddot{u}_i^n = \sum_{m=1}^{M(i)} f_{iq}(u_m^n(X_m,t^n) - u_i^n(X_i,t^n), X_m - X_i,t^n) V_m + b_i^n
\]  

(8)

where superscript \( n \) indicates the time step number, subscript \( i \) denotes the material point \( X_i \), summation range \( M(i) \) is the number of associated family members of material point \( X_i \), and \( f_{iq} \) indicates the interactions between material point \( X_i \) and its associated family member. To discretize the left-hand side, the explicit central finite difference method was used in this study.

\[
\dot{u}_i^n = \frac{u_i^{n+1} - 2u_i^n + u_i^{n-1}}{\Delta t^2}
\]

(9)

where \( \Delta t \) is a constant time step which is required to satisfy the stability condition. In this study, the time step was calculated using reference [50].

\[
\Delta t < \sqrt{\frac{2\rho}{\sum_{p} V_p c_p}}
\]

(10)

Similarly, Equation (8) should be rewritten as a finite summation

\[
\psi(X,t) = 1 - \frac{\sum_{m=1}^{M(i)} \mu(t,\eta,\zeta) V_m}{\sum_{m=1}^{M(i)} V_m}
\]

(11)

In isotropic materials, the interaction forces between the material points within the horizon are independent of direction. However, it is required to consider the directional dependency in the composite structure to calculate these forces. Therefore, to model a fiber-reinforced composite structure in which the fiber direction is \( \gamma \), two different bond constants should be defined. These bond constants are called the fiber bond and matrix bond. As depicted in Figure 2, the fiber bond describes the interaction between two material points along the fiber direction. However, the matrix bond introduces the interaction between the material points which are not along the fiber direction. The fiber bond constant is indicated by \( c_f \) while the matrix bond constant is denoted by \( c_m \). The fiber direction is specified by \( \gamma \).

![Figure 2. Fiber bond and matrix bond configuration in unidirectional composite.](image-url)
The fiber bond and matrix bond are given as the following:

\[ c_f = \frac{2E_1(E_1 - E_2)}{\left(E_1 - \frac{1}{2}E_2\right)\left(\sum_{m=1}^{q} \zeta_{qi}V_q\right)} \quad c_m = \frac{8E_1E_2}{\left(E_1 - \frac{1}{2}E_2\right)l}\delta^3 \]

(12)

where \(E_1\) and \(E_2\) are the elastic material properties of the unidirectional composite, \(\zeta_{mi}\) is the distance between the material points \(X_i\), \(q\) is the total number of material points along the fiber direction, and \(l\) is the thickness of the unidirectional composite. The bond constant \(c\) is obtained on the basis of the directional dependency.

\[ c = \begin{cases} 
  c_f + c_m & \text{if } \theta = \gamma \\
  c_m & \text{if } \theta \neq \gamma
\end{cases} \]

(13)

The critical stretch for a unidirectional composite is dependent on the fiber direction. The critical stretch can be defined on the basis of the fiber bond and matrix bond. The critical stretch for the failure of matrix bond and fiber bond is expressed as [50]

\[ S_f = \sqrt{\frac{10G_f}{\pi c_f \delta^5}} \quad S_m = \sqrt{\frac{10G_m}{\pi c_m \delta^5}}. \]

(14)

In Equation (14), the critical energy release rates are denoted by \(G_m\) and \(G_f\), respectively.

3. Results

The Peridynamic simulations were conducted on unidirectional virtual composite plates containing one, two, and four open holes with different orientations. The effects of the hole orientations and fiber direction were studied on the crack propagation and strength of the composite plates. To validate the PD results, the strength and crack propagation path of the open-hole composite plates were compared with the results from the experimental study. Furthermore, the effects of the degraded material properties on the strength of the unidirectional composite plates were considered. To conduct this study, the degraded material properties obtained from Part I were used to calculate the updated bond constant around the holes.

3.1. Geometry of the Problem

Unidirectional plates with 305 mm in length, 38 mm in width, and 1 mm in thickness with five different hole configurations were considered in the present study. All hole diameters were 6 mm and the distance between the holes was 19 mm side-by-side. Figure 3 illustrates the problem geometry adopted in this study. As shown in Figure 3, there were different orientations of open-hole unidirectional plates with 0\(^\circ\), 45\(^\circ\), and 90\(^\circ\) fiber directions.

3.2. Peridynamic Simulation

The problem domain or space was uniformly discretized in this technique in such a way that all the nodes had an identical elementary volume. The model had 0.8 mm \(\times\) 0.8 mm grid spacing. The unidirectional plates were under the uniform velocity of 2 m/s. The time step was selected as \(\Delta t = 2 \times 10^{-8}\) s. The material properties of the carbon/carbon unidirectional composite are listed in Table 1. The engineering material along and perpendicular to the fiber direction were calculated using the micromechanics concept [41]. The elasticity modulus along and perpendicular to the fiber direction were \(E_1 = 116\) Gpa and \(E_2 = 8.5\) Gpa, respectively. The Poisson’s ratio was 0.33 and the density was 1580 kg/m\(^3\).
The Peridynamic method was applied to the unidirectional composite plates with one hole for the 0°, 45°, and 90° fiber directions. The obtained results are depicted herein.

The PD simulation result for unidirectional composite plates with one hole had good agreement with data available in the literature [36]. According to the results, the crack was approximately initiated at 24,910 N, 2500 N, and 1779 N for the UD plates with the 0°, 45°, and 90° fiber directions, respectively. Additionally, the strength of the UD plates with 0°, 45°, and 90° fiber directions was 31,138 N, 3269 N, and 1890 N, respectively. As shown in Figure 4, the strength and crack initiation load predicted from the unidirectional composite plate with 0° fiber direction was higher than the unidirectional composite plates with 45° and 90° fiber directions. This could be a result of the angle of the applied load with the fiber direction on the composite plates. For the plate with 0° fiber direction, the applied load was along the fiber direction. Therefore, the load was mostly carried out through the fibers and the final failure occurred in a higher load compared to the plate with the nonzero fiber direction. However, more matrix than fiber contributed to carrying the load in the unidirectional plates with 45° and 90° fiber directions.

For further study, the crack propagation and strength of the unidirectional composite plates were studied by the PD method with 0°, 45°, and 90° fiber directions with two horizontal holes, two vertical holes, four holes in a square array, and four holes with a diamond array. Figure 5 shows the simulation results for the plates with two horizontal and vertical arrays with different fiber directions. As shown in this figure, the crack initiation occurred approximately at 3278 N, 1606 N, and 1334 N, for the UD plates with two horizontal holes with 0°, 45° and 90° fiber directions, respectively. Moreover, the strength of the UD plate with two horizontal holes with 0° was 20,907 N, which was higher than the plates with 45° (2104 N) and 90° (1428 N) fiber directions. The results show that the angle of the applied load with fiber direction has a significant effect on the crack initiation and strength of the UD plate. The results obtained for the plate with two vertical holes had the same tendency. The crack initiation and the strength of the plate with two vertical holes was higher than the plates with 45° and 90° fiber directions. For the plate with two horizontal holes with 0° fiber direction, the cracks propagated between holes at 11,339 N once the cracks already initiated at 3278 N reached the end of the plate. For the plates with vertical holes with 90° fiber direction, the results showed that cracks started...
to propagate at 1205 N from one side of each hole. Once the crack reached the end of the plate, the new crack started to initiate at 1294 N on another side of the holes.

![Figure 4](image)

**Figure 4.** Observation of crack propagation in unidirectional composite plates with one hole for three different fiber directions.

Additionally, the crack initiation occurred in the lower loads for the plates with two vertical holes (1659 N, 1606 N, 1334 N for 0°, 45°, and 90° fiber directions, respectively) rather than the plates with two horizontal holes. The results showed that the plates with two horizontal holes were able to carry more loads until failure occurred compared to the plates with two vertical holes with the same fiber direction because of the hole arrangement. The holes are closer to the edges in the plates with two vertical holes compared to the plates with two horizontal holes. The final failures were calculated at 20,907 N, 2104 N, and 1428 N for the plates with two horizontal holes with 0°, 45°, and 90° fiber directions, respectively.
On the other hand, the failure loads were obtained at 16,014 N, 1975 N, and 1334 N for the plates with two vertical holes with 0°, 45°, and 90° fiber directions, respectively.

As shown in Figure 6, the cracks started initiating at 8647 N, 1459 N, and 565 N for the plates with four diamond hole arrangements with 0°, 45°, and 90° fiber directions, respectively. In addition, the strength of the plates was calculated at 17,793 N, 1953 N, and 1188 N with 0°, 45°, and 90° fiber directions, respectively. However, the crack initiation for the plates with four diamond hole configurations with 0°, 45°, and 90° fiber directions occurred at 5187 N, 1032 N, and 743 N, respectively. The strength of the plates was computed at 12,900 N, 1379 N, and 899 N for the 0°, 45°, and 90° fiber directions, respectively. Comparing the crack initiation load of the plates with the square configuration to the plates with the diamond configuration revealed that the crack initiation started at a lower load for the plate with the diamond configuration. Moreover, the strength of the plates with a square hole configuration was higher compared to the plates with a diamond configuration for all the fiber directions.

As concluded for the previous cases, for the plates with two horizontal and vertical configurations, the angle between the applied load and fiber direction had a significant effect on the crack initiation and the strength of the UD plates. For the plates with four square holes configurations, the plate with the 0° fiber direction had the maximum strength (8647 N) and crack initiation load (17,793 N) compared to the plates with 45° and 90° fiber directions. The same results were obtained for the plates with the four diamond holes configuration. In addition, for the plate with the four square and diamond holes configuration, the cracks propagated between holes once the cracks which had already initiated at the very beginning reached the end of the plate. As shown in Figure 6a, this phenomenon occurred at 12,135 N, 1690 N, and 970 N for the 0°, 45°, and 90° fiber directions, respectively. The results obtained for the plates with the four diamond holes configuration followed the same tendency.

3.3. Validation

The experimental study was carried out to validate the PD simulation results. Three specimens for each case were planned for tensile testing. As shown in Figure 7, the experimental study was designed for five different holes configurations of unidirectional composite plates with 0°, 45°, and 90° fiber directions.
Comparing the crack initiation load of the plates with the 0°, 45°, and 90° fiber directions had a good agreement with PD simulations. As concluded for the previous cases, for the plates with two horizontal and vertical holes, the angle between the applied load and fiber direction had a significant effect on the crack initiation and the strength of the UD plates. For the plates with four square holes configurations, the plate with the 0° fiber direction had the maximum strength (8647 N) and crack initiation load (17,793 N) compared to the plates with 45° and 90° fiber directions. The same results were obtained for the plates with the four diamond holes configuration. In addition, for the plate with the four square and diamond holes configurations, the plate with the 0° fiber direction had the maximum strength (8647 N) and crack initiation load (17,793 N) compared to the plates with 45° and 90° fiber directions. The average of failure loads for each case is listed in Table 2.

The tabs were attached to the specimens with Epoxy 9394 from Loctite (48 h curing time). Specimens were tested with the tensile–tensile fatigue loading on an MTS 810 machine. The increment of the load was 2 N/s.

To validate the obtained PD results, the numerical simulations were compared to the experimental study. The specimens were scanned with the scanning acoustic microscope (SAM). All SAM images were taken at room temperature and using a 100 MHz acoustic transducer with a lower and higher frequency range of ~25 MHz to ~500 MHz, with a peak near ~100 MHz. The results obtained are presented in Figure 8. Evidently, the crack paths obtained from PD simulations followed the same pattern as the experimental study. This showed that the PD simulation can predict the crack path accurately. As depicted in Figure 8, the crack path of the unidirectional plates with different holes configuration with 0°, 45°, and 90° fiber directions had a good agreement with PD simulations.

The tensile test was performed for each and every specimen. The failure loads were measured for the unidirectional plates with different hole orientations and two fiber directions (the 45° and 90° fiber directions). The average of failure loads for each case is listed in Table 2. The strength of the UD plates from PD simulation without considering degraded material properties were compared with the experimental data. Figure 9 shows the com-

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**Figure 7.** Unidirectional composite samples with (a) 0° fiber direction with different hole orientations, (b) 90° fiber direction with different hole orientations, (c) 45° fiber direction with different hole orientations.

**Figure 8.** Validation of crack propagation in unidirectional plates with different fiber directions and (a) two horizontal holes, (b) two vertical holes, (c) four square holes, and (d) four diamond holes.
parison of the failure loads of the unidirectional plates with different hole orientations. In this study, the strengths of the UD plates with 0° fiber direction were not reported since the failure loads were not measurable in this case because of the temporary malfunction of the MTS machine.

Table 2. Failure loads of unidirectional plates with different hole orientations and fiber directions obtained by the tensile test.

| Hole Orientations       | Fiber Direction | Failure Loads (N) |
|-------------------------|-----------------|------------------|
| One hole                | 45° 3136        |
|                         | 90° 1797        |
| Two horizontal holes    | 45° 1975        |
|                         | 90° 1343        |
| Two vertical holes      | 45° 1868        |
|                         | 90° 1221        |
| Four holes with square array | 45° 1855    |
|                         | 90° 1141        |
| Four holes with diamond array | 45° 1323    |
|                         | 90° 832         |

Figure 9. Comparison of failure loads of Peridynamic (PD) simulations and experiments.

3.4. Quantifying the Strength of the UD Plate with One Hole in the Presence of Microvoid (Effect of Microscale Defects)

Making holes in composite materials may cause material degradation at the vicinity of their edges. Consideration of the degraded material properties around the hole edges is necessary to predict the strength of unidirectional composite plates with an open hole accurately. To fulfill this requirement, the bond constant for the degraded area must be updated. This can be performed by quantifying the local material properties degradation of composite plates using micromechanics. According to established literature [41], the effective material properties for the unidirectional (UD) carbon/carbon composite materials were calculated for different percentages, shapes, sizes, and locations of voids. Figure 10 shows the location of the considered material degradation around the hole and the different types of voids in the composite materials.
According to the literature [37], the effective material properties were calculated for different percentages, shapes, sizes, and locations of voids. The engineering materials were computed on the basis of the following formulation.

\[
E_{33}^{\text{eff}} = C_{33}^{\text{eff}} - \frac{2}{C_{11}^{\text{eff}} + C_{12}^{\text{eff}}} E_{11}^{\text{eff}} = C_{11}^{\text{eff}} - \frac{(C_{23}^{\text{eff}})^2}{C_{23}^{\text{eff}} - \frac{2}{C_{33}^{\text{eff}}}} \left( C_{11}^{\text{eff}} + 2 C_{12}^{\text{eff}} \right) C_{12}^{\text{eff}} \right) 
\]

(15)

Figure 11 shows the effective material properties for the different types of microvoids. The degraded material properties were applied to the problem by recalculating the bond constant for those material points located around the hole edge. The engineering constants for unidirectional composite plates were calculated by Equation (15). Hence, the updated bond constants for degraded material points were calculated using Equation (12). In this study, the bond constants were calculated when the degraded area had 1%, 2%, and 3% void content. The average value of the Kirchhoff moduli is listed in Table 3.

![Figure 10. Degraded material properties area and different types of void in the composite materials.](image)

![Figure 11. Effective material properties for different types of microvoids.](image)
The PD method was employed using the updated bond constant for the degraded area. Figure 12a depicts the change percentage of the failure loads in the degraded unidirectional plates and pristine ones.

The results showed that the degraded material properties had less of an effect on the unidirectional plates with 0° fiber direction in comparison to the composite plates with 45° and 90° fiber directions, since the void content had less of an effect on the elastic modulus along the fiber directions. Figure 12b shows the strength of the UD plates with the one rivet-hole configuration, but with a different percentage of void content near the vicinity of the rivet-hone. PD simulations were concluded without the effect of the multiscale void content, and with 1%, 2%, and 3% void content observed around the rivet-hole. In Figure 12b, the experimentally observed strength is also presented side-by-side for an effective comparison. Since the void percentages around our specimens were not known, the experimental results can not be compared with any particular void content. Experimental data were obtained from the three specimens, and an error bar was obtained with a strength of 3136 (±52) N and had a variation around the average value of 3136 N, assuming normal distribution. The results showed that the experiment results had more correlation and lower error with the UD plate with 3% void content around the hole. Vice versa, this method could even predict the void content around the hole, even though that was not the intent of this study.

4. Conclusions

In this study, strength of unidirectional (UD) composite plates with an open rivet-hole was predicted more accurately by incorporating the effect of degraded material properties around the hole due to local defects (e.g., microvoids). The Peridynamic (PD) modeling approach was employed to simulate the UD plates with five different configurations of rivet holes. First, the strengths of the plates and the crack initiations in the UD plates
were predicted, without considering the effect of microvoids around the holes. The results obtained from PD simulation were validated with the experimental data obtained from MTS machine and scanning acoustic microscope (SAM). The results showed that the PD simulation could successfully predict the strength and the could predict the crack path in unidirectional composite plates under tension. For the 45° fiber direction, the strength of UD plates were predicted to be 3269 N, 2104 N, 1975 N, and 1379 N for the cases with one, two horizontal, two vertical, four square, and four diamond hole configurations, respectively. The results showed that the plate with one hole had the maximum strength and the plate with four holes with diamond configurations had the minimum ultimate strength. This trend was also observed in the plates with 0° and 90° fiber directions. Crack initiation in the plates with a 45° fiber direction and four square hole configurations occurred at 1032 N, which was the lowest, compared to the load when the other plates with the same fiber direction and different hole configurations started to show the sign of cracks. Additionally, the crack propagated between the holes at a certain load only when the crack reached at the end of the plate for all the hole configurations. For example, the plate with a four square hole, the crack propagated between the holes at 12,135 N, 1544 N, and 698 N for the 45° and 90° unidirectional composite plates, respectively. Further, incorporating the degraded material properties due to microvoids using updated/degraded elastic modulus near the vicinity of the hole, the PD-predicted strength of the plate with one hole had a better correlation with the experimental data. Further, the results showed that the degraded material properties obtained from the effect of microscale defects had a certain effect on the prediction of the ultimate strength. Such effects on 0° fiber direction were lower in comparison to the composite plates with 45° and 90° fiber directions, since the void content had less of an effect on the elastic modulus along the fiber directions.

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