Onset of Resin Micro-cracks in Unidirectional Glass Fiber Laminates with Integrated SHM Sensors: Numerical Analysis

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The embedment of micro-sensors and micro-devices into composite laminates for structural health monitoring systems leads to stress/strain concentrations due to geometrical and material discontinuities around such embedded inclusions, with high potential to initiate premature failures. This article presents the efforts to estimate the effects of these stress/strain concentrations induced by the integration of rectangular-shape sensors within unidirectional fiber-glass composites. The micro-crack initiation sites and the failure load are predicted using finite-element simulations. Good agreement has been found between the numerical results and the experimental findings presented in an accompanying paper.

Keywords  structural health monitoring · embedded sensor · stress/strain concentration · finite-element analysis · matrix micro-cracking · composites

1 Introduction

Adding health monitoring functionalities by integrating micro-devices within composites brings out structural integrity concerns about the effect of the inclusions on the load-carrying capability of the resulting structures, their expected service lives, and the associated failure mechanisms. The presence of the embedded micro-devices causes material and geometric discontinuities, which can be responsible for unwanted stress/strain concentrations with consequent stiffness reduction and degradation of the overall material performance, necessitating the study of the mechanical interaction among the host material, the embedded devices, and their interfaces.

A number of experimental studies [1–6] have been conducted to assess the strength and failure modes of composite materials with embedded devices such as silicon chips, piezoelectric (PZT) sensors, or fiber-optic sensors (FO). From these studies it appears that in cases where the thickness of the inclusion does not alter significantly the through-the-thickness geometry of the host material, the resulting stress concentration is rather small, and thus has negligible effects on the material integrity. However, in cases where

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the integrated devices are not suitably small, the strength reduction as well as the resulting damage mechanisms needs to be investigated and quantified.

Several numerical studies have addressed the effects of embedded optical fiber sensors on the failure mechanisms of the composite laminates. Dasgupta et al. [7] have used the Rayleigh–Ritz method to investigate the effect of the geometry of the resin-rich region around the FO sensors embedded in laminated composites. The predicted geometry was discretized for finite element analysis to obtain stress information in the vicinity of the resin pocket. Levin and Nilsson [8] have performed finite element analyses to determine the local stress field in a tensile composite specimen with an embedded Extrinsic Fabry-Perot Interferometer (EFPI). The actual reduced local fiber volume content around the sensor was determined based on image analysis technique and used in the computational model. Their results showed that the sensor-coating and the coating-composite interfaces are the sites where failure is initiated due to the stress concentration caused by the cavity in the EFPI-sensor. Eaton et al. [9] have analyzed the stress and strain concentrations in and around an optical fiber embedded in composite laminates. Three general laminate constructions were studied. For the case of optical fibers embedded perpendicularly to the neighboring fibers, they observed that significant stress concentration occurred in the distorted plies representing a shift of the load path away from the resin pocket tip. Recently, Shivakumar and Bhargava [10] have studied the effect of an ‘eye’-shaped resin pocket defect produced by embedding a FO sensor perpendicularly to the reinforcing fibers. The fiber waviness due to the embedment of the sensor is represented in their finite-element study by using a local element coordinate system parallel to the distorted fibers. Based on the computed stress concentration factors and residual curing stresses, the fracture stress was calculated using the maximum stress criterion. Their results indicate that, under a tensile loading, the initial failure is by transverse matrix cracking at the resin pocket root, which then leads to a final fracture by fiber breakage.

Among the few numerical studies on embedded rectangular implants, Chow and Graves [11] investigate the stress and displacement fields near a soft implant in a laminated composite material. The implant is embedded by cutting several plies of the composites. Their results indicate that the interlaminar stresses are an order of magnitude lower than the stress representing the applied far-field load and the stress concentration factor is dependent on the stacking sequence of the laminates. Singh and Vizzini [12] have analyzed the interlaminar stress state surrounding an interlaced, active piezoceramic actuator embedded within a unidirectional composite laminate. Their finite element model appears to be insensitive to the transition resin layer thickness and the resin-pocket length when the length is greater than seven times the ply thickness. They conclude that interlacing increases the strength of the composite structure with embedded actuators by redistributing the load around the inclusion and the host-inclusion interface. They also state that the delamination in the host composite is virtually independent of whether or not the inclusion is active.

A previous experimental study has been conducted by Ghezzo et al. [13] to investigate the micro-crack initiation within S2 glass–epoxy laminates with embedded dummy sensors under quasi-static tensile loading conditions. Based on the experimental results obtained, the present paper aims at simulating numerically the interaction between the fiber glass–epoxy laminate and the embedded (simulated) sensor. The objective is to investigate numerically the impact on the local stress and strain fields of the resin-rich area and the fiber distortion due to the embedment of a rectangular implant. In addition, von Mises and Drucker–Prager criteria are applied to identify and locate the damage initiation sites. The finite element simulation results are then compared with experimental data.

2 Finite Element Model

2.1 Idealized Model for the Host-Sensor System

In the experiments described in [13], a 0805 chip resistor is embedded into a composite
lamine to simulate an embedded sensor. The composite laminate is made from S2/BT250E-1LV unidirectional glass-epoxy prepreg. The fiber volume fraction is ~53%. An embedded rectangular-shaped simulated sensor in a fiber-reinforced composite creates a resin pocket, as shown in the previous work [13]. The dimensions of the resin pocket are measured off the micrographs of sectioned samples.

The 0805 chip resistor (shown in Figure 1), whose dimension are 2.03 mm (\(L_S\)) by 1.27 mm (\(W_S\)) by 0.55 mm (\(T_S\)), is placed with its length aligned with the fibers direction. The protective polymeric coating material in this analysis is assumed to have the same material properties as the composite matrix and the effect of the resistive film is ignored.

The idealized 2D model is shown in Figure 2. The length (\(L\)), width (\(W\)), and thickness (\(T\)) of the model are 150, 25.4, 3 mm, respectively. \(H_D\), the height of the region where the fibers are disturbed from axially is ~0.55 mm, based on the micrographic measurements. The resin pocket region's half-length, \(L_{RP}\), is about 2.7 mm. The thin transition resin layer between the sensor and the composite areas, acting as a compliant shear layer, has the thickness \(T_{TR}\) = 0.01 mm. The resin pocket root has an angle of 1.21 degree. The radius of curvature of the sensor fillet angle (\(R_C\)) is ~0.06 mm. The length (\(L_C\)) of the region covered by the metal coating is ~0.406 mm. The three metal coating layers (from outer to inner: tin solder plating, nickel plating, copper inner electrode) are assumed to be 0.01 mm thick for each layer. The baseline model (Model 1) contains six different material areas, namely sensor substrate, three metal coating layers, epoxy resin matrix, and fiber glass/epoxy composite. The curved lines represent the profile of the reinforcing fibers. The properties of each material are listed in Tables 1 and 2.

2.2 Finite Element Analysis

Owing to the symmetry of the idealized model, only one quarter of the sample has been considered (Figure 3). The center of the embedded simulated sensor is used as the origin.
of the coordinate system, with the length, thickness, and width directions defining the $x$-, $y$-, and $z$-axes, respectively.

A plane strain state has been assumed. Moreover, since the effect of the fiber distortion in $x$–$z$ plane was found to be much smaller than that in the $x$–$y$ plane, as proven by the experimental observations in [13], it has been ignored in this work.

A 3D model has also been studied and the results are compared with those given by the 2D plane strain model, but no significant improvement has been found in terms of the stress and strain results.

Four-node quadrilateral plane strain elements are mostly used in this numerical analysis. In addition, three-node triangular elements are used to model the tip of the resin pocket. Figure 4 shows the local finite-element mesh around the resin pocket for the baseline model (Model 1).

As it can be seen, a finer mesh is used for the domain around the sensor and particularly the resin pocket root, where maximum stresses are expected. The element shape in these critical areas is carefully chosen to better approximate the ply distortion next to the inclusion.

For each element in the composite region where fiber distortion occurs (elements modeling
the area surrounded by the dashed lines for \( y \leq H_D \) in Figure 3), a local element coordinate system is set up that follows the fiber distortion. This is important for simulating the change of the material properties due to the deviation of the fiber direction from that of the global \( x \)-axis.

In the finite-element analysis, 8353 nodes and 8153 elements are used. Several coarse mesh analyses have also been conducted to check the accuracy of the results.

Symmetric displacement-boundary conditions are used in the \( x \)- and \( y \)-directions, and a uniform displacement equal to 1% of the model length is imposed at the far ends in the longitudinal direction to produce a 1% nominal overall strain. The remote stress, \( \sigma_0 \), is calculated by averaging the resultant end forces, resulting in a stress value of 476.0 MPa for the baseline case.

In addition to the baseline case, analyses were carried out to study the sensitivity of the finite element model to the variation in the resin pocket length and transition resin layer thickness. The effect due to the increase of the fiber volume content around the embedment was also studied.

3 Results and Discussion

3.1 Baseline Case

3.1.1 Strain and Stress Fields in Tension The model for the baseline case is identified as Model 1. Figure 5(a)–(c) show the contours of the three strain components around the region where material and geometrical discontinuities are present. The maximum longitudinal and shear strains appear at the sensor corners within the resin-coating interface (resin rich region). The longitudinal strain is \( \sim 9.17\% \), while the shear strain is \( \sim 22.65\% \) for the applied 1% overall strain. The minimum transverse strain (in compression) also concentrates at the sensor corners, and is about \(-7.54\%\).

Among the three strain components, the shear strain has the maximum value. Since the neat epoxy resin can carry the least strain among all the materials in the model, shear debonding at the resin-sensor coating interface is expected to be the main cause of failure initiation. This is consistent with our experimental observations. Unlike Shivakumar and Bhargava’s work [10], the strains at the resin pocket root are much smaller than the strains in the sensor neighborhood. The reason of the discrepancy stands on the different materials analyzed and different geometry inclusions. In this specific case, the simulation results together with the experimental observations preclude the tip of the resin rich area as a potential site for damage initiation.

All the stress components were also computed for the externally imposed nominal longitudinal strain of 1%. This nominal strain is equivalent to a 476.0 MPa stress in tension. Without considering the sensor area (load-carrying capability is
generally high), the maximum longitudinal stress appears in the composite-resin interface at the composite region where fibers start to be disturbed. The stress concentration factor calculated by normalizing the maximum longitudinal stress with the averaged remote stress ($K = \sigma_{xx}/\sigma_0$) is about 2.54. The maximum and minimum transverse stresses occur in the sensor area. At the sensor corner, from the upper edge to the right edge, the stress changes from compression to tension. Moreover, the maximum shear stress in composite and resin-rich regions concentrates at the sensor corner in the resin-sensor coating interface. Its value is $\sim 311.1$ MPa for a

Figure 5  The $\varepsilon_{xx}$ (a), $\varepsilon_{yy}$ (b), and $\varepsilon_{xy}$ (c) strain contours around resin pocket region.
476.0 MPa remote stress, while the maximum value computed according to the von Mises criterion is ~570.2 MPa.

The stresses along the resin-composite interface \(0 \leq x \leq L_S/2 + L_{RP}\) and resin-sensor coating interface \(L_S/2 - L_C \leq x \leq L_S/2\) are highly critical since they may trigger rapid failure by delamination. The distribution of the stresses is shown in Figure 6(a)–(c). The plots are normalized by the applied remote stress, \(\sigma_0\), and the \(x\) coordinate is normalized by the sensor thickness, \(T_S\).

From these plots, the stresses along the resin-composite and resin-sensor coating interfaces generally have the same trend, with the magnitude being higher in the latter case. The longitudinal and transverse stresses exhibit steep gradients at point A where the metal coating layer starts and at point B where the metal coating bends down. The maximum stresses appear at the sensor corner area. At the end of the resin pocket (point C), the transverse stress increases. However, based on the transverse material strength resulted from the experimental characterization and reported in Tables 1 and 2, this small increase is found to be not sufficient to cause fiber-matrix splitting. The shear stresses along both interfaces show sharp rises at the sensor corner, decreasing monotonically away from the singular point. The three stress components at the critical location, \(x \approx 1.75T_S\), close to point B, where the maximum von Mises stress is reached, are 37.1 MPa (\(\sigma_{xx}\)), -199.3 MPa (\(\sigma_{yy}\)), and 307.1 MPa (\(\sigma_{xy}\)), respectively. The shear stress component is dominant.

### 3.1.2 Curing Stresses

In this study, the effect of the curing process on the residual stress within the material is taken into consideration.

The composite panels were cured from 250°F (121.11°C) to 75°F (23.89°C, the room temperature). The first 90°F temperature drop has little impact on the residual stresses due to a high viscoelastic relaxation. Therefore, the curing stresses induced from 160°F (121.11°C, based on the producer’s material data sheet) to 75°F (23.89°C) are computed. The variation of the curing stresses along the resin-composite interface and resin-sensor coating interface are plotted in Figure 7(a)–(c). From these plots it appears that the longitudinal and the transverse curing stresses...
have distributions similar to the corresponding stresses due to the applied tensile deformation, as shown in Figure 6(a) and (b). These two stress components in case of application of external tensile load contribute to expedite the failure initiation. The curing shear stress at point A has similar effect. On the other hand, the shear component of the curing stress at point B where the maximum shear strain generally occurs, as it was seen in the previous sections, is in the direction opposite to the shear stress due to the applied tensile load. Therefore, it has positive effect on the material strength, increasing the resistance to the failure initiation at this particular point. However, it is the combination of the three components of the stress resulting from the superposition of the stress due to the application of external tensile load and to the fabrication process that has to be considered for the failure initiation, as it will be presented in Section 4.

3.2 The Effect of the Transition Resin Layer Thickness

The baseline model was modified to evaluate the sensitivity to the resin layer thickness ($T_{TR}$) and the resin pocket length ($L_{RP}$). The stress state is investigated for the transition resin layer thickness ranging from 0.0067 to 0.0167 mm. The variations of the normalized longitudinal, transverse, and shear stress components along the resin-sensor coating interface with respect to various resin layer thicknesses are shown in Figure 8(a)–(c). The trend in the stress plots remains similar to the baseline case ($T_{TR} = 0.01$ mm). The variation of the resin layer thickness has a more significant effect on the shear stress in comparison with its effect on the other two stress components. The maximum shear stress in the resin-sensor coating interface experiences a 10.5% decrease for a 66.7% increase in the resin layer thickness and a 9.5%
increase for a 33.3% decrease in the resin layer thickness. In conclusion, the finite-elements model results seem to be not sensitive to the thickness chosen for the transition resin layer within the considered range.

### 3.3 The Effect of the Resin Pocket Length

The effect of resin pocket size on the stress state was also investigated. The resin pocket lengths varying from 1.35 to 3.375 mm were studied. The variations of the normalized longitudinal, transverse, and shear stresses along the resin-sensor coating interface are shown in Figure 9(a)–(c). The stress distributions for different resin pocket lengths remain the same as in the baseline case (\( L_{RP} = 2.70 \text{ mm} \)). The transverse stress is more sensitive than the other two stress components. The maximum transverse direction compressive stress in the resin-sensor coating interface experiences a 5.1% decrease for a 25% increase in the resin pocket length and a 23.5% increase for a 50% decrease in the resin pocket length. From these results it appears that the \( L_{RP} \) value does not have a profound impact on the stress results.

### 3.4 Effect of Local Fiber Volume Content Increase

The experimental observations show that the fibers are more closely packed around the inclusion due to the embedding process. This fact may affect the local composite material properties. To simulate the effect due to the change of the fiber volume content in the fiber disturbance region (\( y \leq H_D \)), a new model, designated as Model 2, was studied. The main difference between Model 1 that has been used so far in the analysis and Model 2 that will be introduced in this paragraph consists on the different material properties that

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Figure 7  Variations of \( \sigma_{xx} \) (a), \( \sigma_{yy} \) (b), and \( \sigma_{xy} \) (c) due to curing along the resin-composite and resin-sensor coating interfaces.
characterize different regions around the inclusion. Instead of a unique homogenized composite region with unique properties as defined in Model 1, the composite area around to the inclusion was divided in different regions with different material properties. From the micro-structural investigations, in fact, we observed that there seems to be a different distribution of the fibers density around the inclusion. The fact is due to the application of pressure during the fabrication process. For simplicity, only two new regions were introduced in Model 2, as shown in Figure 10. Region 1 was assumed to contain 70% of fibers in volume and, therefore the mechanical properties of the homogenized composite in that area are those that characterize an extremely high concentration of fibers. Region 2, instead, is considered as a transition region. The mechanical properties of this area were computed as the average of those obtained for the region where we defined the presence of 70% fibers in volume and the region far from the inclusion where 53% fibers volume fraction is the value found experimentally. The lengths of the two regions are 1.5 and 1.7 mm, respectively. The material properties for these two regions are listed in Table 3. The rest of the model is the same as Model 1. The applied load is still equivalent to a 1% nominal longitudinal strain.

The stress and strain fields computed for Model 2 are similar to those of Model 1. The averaged remote stress, $\sigma_0$, corresponding to the applied 1% nominal strain is about 477.2 MPa. As for Model 1, the maximum von Mises stress within the resin layer appears at the sensor corner in the resin-sensor coating interface. Its value is $\sim$575.7 MPa. The distribution of the stresses along the resin-sensor coating interface, where micro-cracking is expected to initiate, is plotted in Figure 11(a)–(c) and compared with the results from Model 1. All the stresses are normalized by the remote stress, $\sigma_0$.

It appears that the variation of the local fiber volume content assigned to the aforementioned
regions in the model and created to reproduce the local fiber distortion around the embedded dummy sensor, is responsible for a change in the stress values (tensile, transverse, and shear) of $5.8\%$ of those of the baseline case (Model 1). Therefore, the increase of computational efforts that Model 2 presents with respect to Model 1 is not worth.

4 Failure Analysis

Since S2 glass fibers have a much higher Young’s modulus than the neat epoxy resin, most of the load is carried by the fibers, so that the ultimate failure strength is mainly determined by the fiber volume fraction.

Embedding micro-sensors and devices without cutting the plies around the implants (also known as cut-out methods) is not expected to have a significant impact on the ultimate failure strength since it does not significantly modify the material properties. The quasi-static tensile characterization of the material [13] shows that the embedment of rigid inclusions causes an averaged decrease of only $2.6\%$ in the ultimate failure strength.

Figure 9 Variations of $\sigma_{xx}/\sigma_{0}$ (a), $\sigma_{yy}/\sigma_{0}$ (b), and $\sigma_{xy}/\sigma_{0}$ (c) along the resin-sensor coating interface for various $L_{RP}$.

Table 3 Material properties used in Model 2.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's modulus (GPa)</th>
<th>Shear modulus (GPa)</th>
<th>Poisson's ratio</th>
<th>Coefficient of thermal expansion($10^{-6}/^\circ{C}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_x$</td>
<td>$E_y$</td>
<td>$G_{xy}$</td>
<td>$\nu_{xy}$</td>
</tr>
<tr>
<td>Region 1 (70% fiber)</td>
<td>61.99</td>
<td>11.66</td>
<td>4.24</td>
<td>0.28</td>
</tr>
<tr>
<td>Region 2</td>
<td>54.90</td>
<td>10.73</td>
<td>3.97</td>
<td>0.29</td>
</tr>
</tbody>
</table>
Moreover, the stress concentration factor of 2.54 is much smaller than the one caused by a 1 mm through-the-thickness hole in the same host laminate, which was found to be about 4 by conducting a numerical simulation of the case. This again suggests that the impact of the embedded dummy sensor on the ultimate strength is rather small.

The curing stresses are very small in comparison with the ultimate failure strength. The impact of the curing effect on the ultimate strength seems to be negligible.
The stress applied at the far end that can initiate local failure is referred to as the failure initiation stress in this work. Based on the stress distribution results for the baseline model reported in the previous section, the stress values that cause the initiation of the failure were calculated both for the composite area and the neat resin area separately.

For the composite domain, the maximum stress criterion is used. Failure is assumed to occur when at least one stress component along one of the principal material axes reaches the value of the corresponding material strength. The criteria are defined as follows:

**Tension failure:**

\[
\sigma_1 = F^c_{1t} \quad \text{or} \quad \sigma_2 = F^c_{2t}. \tag{1a}
\]

**Compression failure:**

\[
\sigma_1 = F^c_{1c} \quad \text{or} \quad \sigma_2 = F^c_{2c}. \tag{1b}
\]

**Shear failure:**

\[
|\sigma_6| = F^c_6. \tag{1c}
\]

Here, the subscripts 1 and 2 refer to the principal material axes of the composite material (which correspond to the local element coordinate system).

For the neat resin area (including the transition resin layer and the resin pocket), the von Mises criterion and the Drucker–Prager criterion are considered. Failure is assumed to occur when the stress components satisfy the chosen failure criterion. The criteria are defined as follows:

The von Mises criterion:

\[
F'_i = (-3J'_2)^{1/2}, \tag{2a}
\]

\[
J'_2 = -1/6[\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2]. \tag{2b}
\]

The Drucker–Prager criterion:

\[
F'_i = \frac{k - 1}{2k} J_1 + \frac{k + 1}{2k} (-3J'_2)^{1/2}, \tag{3a}
\]

\[
J_1 = \sigma_1 + \sigma_2 + \sigma_3, \tag{3b}
\]

\[
k = \frac{F'_c}{F'_i}, \tag{3c}
\]

where \(\sigma_1, \sigma_2,\) and \(\sigma_3\) denote the principal stresses, which are the eigenvalues of the stress components in the global coordinates. If the curing effect is included, each of these global stresses is the sum of the stress due to the externally applied tensile load and the thermal curing stress. \(F'_i\) and \(F'_c\) are the tensile and compression strengths of the epoxy resin, respectively. The Drucker–Prager criterion is a more suitable criterion for describing the failure of composite resins due to multi-axial stress states, than the von Mises criterion [14].

Using these criteria and the material strength given in Table 2, the failure initiation stress was predicted for the baseline model. Table 4 summarizes the prediction results. Since the failure always appears first in the resin area, only the results concerning the resin area are presented.

The site of failure initiation is located at the sensor corner within the resin-sensor interface independently of the criterion chosen. This result is consistent with the experimental observations. The overall impact of the curing stresses seems to expedite the failure initiation.

The failure mode is complicated if the curing effect is included, since the shear stress is not

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**Table 4**  
**Failure initiation stress.**

| Prediction (MPa) |  |  |  | Experiment (MPa) |
|-----------------|-----------------|-----------------|--------------------|
| **Von Mises**    | **Drucker–Prager** |
| Curing stress   | Curing stress   | Curing stress   | Curing stress   | Experiment (MPa) |
| Not included    | Included        | Not included    | Included        | Experiment (MPa) |
| 62.6            | 52.2            | 79.6            | 51.1            | 46–106            |
dominant any longer. From the experimental point of view, the failure prediction based on the numerical results without considering the curing effect is closer to the real case where failure in a shearing mode has actually been observed.

5 Conclusions

The presence of the embedded micro-sensors and electronics in laminated composites is expected to initiate premature failure. Complex micromechanical interactions occur at the fiber glass/epoxy laminate and the embedded dummy sensor interfaces as demonstrated in a previous experimental work. Guided by the experimental findings, a finite element analysis has been conducted to study the effects of the embedded simulated micro sensors on the stress/strain fields and failure mechanisms within the host composite laminate. According to the results obtained, under a tensile loading, the initial failure is expected to be matrix cracking at the sensor corner in the resin-sensor coating interface. The influence of variables such as the thickness of the sensor-composite interface, which consists in a thin layer or resin all around the inclusion and the length of the resin pocket region due to the fabrication process and whose size has been previously observed in micro-structural investigations has also been investigated. Particularly, the sensitivity analyses show that the transition resin layer thickness and the resin pocket length seem to not have a profound impact on the distribution of the stress obtained in the case that we defined as baseline model. Also, if the increase of the fiber volume content around the embedment due to the pressure applied during the fabrication process is taken into account, the effect on the stress distribution and failure is also very small.

A considerable result is instead attributed to the fact that the presence of residual stresses which forms in the last part of the resin curing cycle when the material cools down to room temperature, tends to expedite the failure initiation. The failure initiation load was predicted using the von Mises and the Drucker–Prager criteria and was found to be very close to the stress at which the acoustic emission events start as presented in the experimental investigation used as reference [13]. Good agreement, therefore, has been found between the numerical predictions and experimental findings in terms of stress at which the micro-cracks start at the sensor corner.

The presence of the embedded micro-sensors and electronics in laminated composites without any special preparation is expected to initiate premature failure. However, the sensor module and the host composite might be designed together so that they would not affect the local structural integrity of the material. This could be done by optimizing the size, shape, and material properties of the sensor module, and by designing the composite to relieve the stress concentration at the sensor-composite matrix interface. This can be performed, for example, by rendering the laminate thicker at the sensor location and therefore providing local reinforcement to those areas where peak values of stress concentration and residual strains can be found.

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