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PROGRESSIVE FAILURE ANALYSIS OF COMPOSITE LUGS

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Abstract. *A methodology is presented for the analysis and failure prediction of lugs manufactured with composite materials under static tension and compression loading conditions in order to provide a numerical tool for the design of these components. The preliminary sizing and laminate selection are initially investigated using a semi-analytical approach based on the classical lamination theory, which is extended to include a stress concentration factor to account for the presence of the lug. This model is combined with a genetic algorithm using an elitist selection scheme to search for viable geometries and lay-ups, which are then studied in more detail using a finite element analysis in Abaqus FE code. Simulations are carried out using an explicit dynamics analysis under quasi-static loading conditions, in which a progressive failure model is implemented as a user-defined material. The progressive failure model allows the prediction of matrix cracking, fiber failure, and delamination at the ply level. During verification using experimental data from the literature, the method was able to predict the failure load of a lug within 3% of the test results. The methodology was later applied to a case study of the design of a composite brace on the landing gear of a narrowbody aircraft.*

Keywords: Composite Materials, Finite Element Analysis, Progressive Damage Analysis, Composite Lug Design.

1. INTRODUCTION

The design and certification of composite parts for primary structures in the aeronautical industry is a challenging process, often requiring extensive experimental testing that impacts the costs and time necessary for the development of the part. This issue is further aggravated in highly loaded components with complex geometries, where the use of thick laminates and the presence of features that induce stress concentration increase the complexity of the analysis.

Lugs are elements widely employed to join aeronautical structures. However, their design is difficult because of the interaction of different failure modes, as shear-bearing, tension, and hoop tension failures. The application of composite materials for these components introduces a new set of problems because of the anisotropy of the material properties. The design should also take into account aspects such as the volume of the component and the integration with adjacent structures. Besides, it is of particular importance to evaluate the strength of the lug and predict its failure modes when the component is part of a primary structure of the aircraft. Progressive damage models can evaluate the extent of the damage and identify the mechanisms that will lead to the failure of the component under the specified loads, offering valuable insights to improve the robustness of the structure.
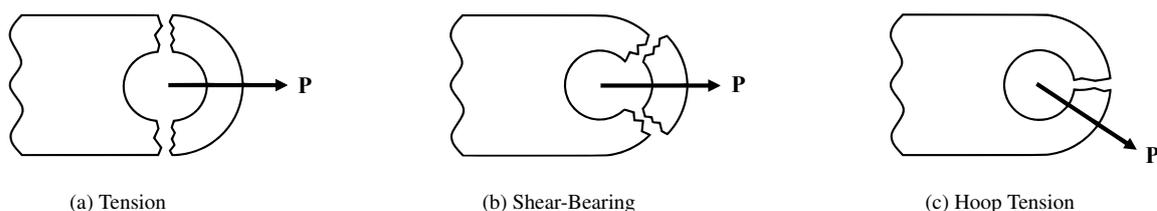

| (a) Tension | (b) Shear-Bearing | (c) Hoop Tension |

Figure 1. Illustration of common failure modes of a lug.

2. PRELIMINARY DESIGN

2.1 Loading conditions

The analyses were based on the lug illustrated in Fig. (2) for tension and compression loading conditions. Transversal, oblique, and out-of-plane loads were not taken into account. Additionally, the formulation of the stress-concentration factor used in the semi-analytical model only evaluated tension failure, as presented in Fig. (1a).
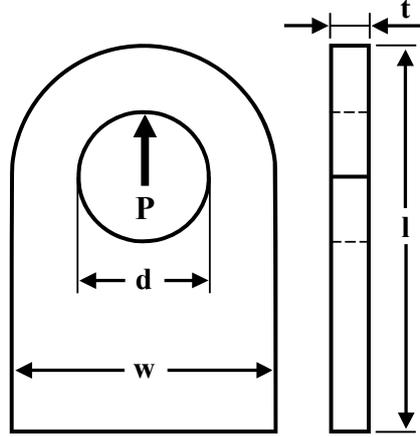
Figure 2. Representation of a typical lug.

2.2 Semi-Analytical Model

Several approaches have been proposed in order to evaluate the design of composite components. Analytical tools are often preferred in the initial design phases of a project since they provide a means to quickly analyze a large number of configurations, thus producing useful information for the preliminary sizing of the part. For this reason, a semi-analytical methodology where the lug is modeled as a stress concentration factor applied to the classical lamination theory was chosen to inspect combinations of lay-ups and geometries regarding the fulfillment of the problem requirements.

The classical lamination theory is a technique to describe the stresses and strains in composite laminates under plane-stress loading conditions (Jones, 2018). Each layer is supposed to be composed of a thin plate of an orthotropic material oriented arbitrarily with respect to the coordinate system of the part. Based on the material properties, orientation, and thickness of each layer and the stacking sequence of the entire laminate, it is possible to describe the relationship between the generalized forces and moments per unit length, N and M, and the resulting mid-plane deformations ε^0 and curvatures κ in the laminate by Eq. (1).

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix} \varepsilon^0 \\ \kappa \end{bmatrix} \tag{1}$$

Matrix A represents the extensional stiffness, D the bending stiffness, and B the bending-extensional coupling stiffness of the laminate. From these results, the stresses σ in each layer can be obtained from the constitutive equations that describe the stress-strain relationship of the material.

$$[\sigma] = [\bar{Q}] \, [\varepsilon] \tag{2}$$

Where $\bar{Q}$ represents the reduced stiffness of each layer, obtained from the properties of the material. The effect of the lug can then be modeled as a stress concentration factor to predict the net section failure of the component (Kassapoglou and Townsend, 2003). Initially, the stress concentration factor of a circular hole in an infinite orthotropic plate is calculated with Eq. (3).

$$K_{TOH}^{\infty} = 1 + \sqrt{\frac{2}{A_{22}} \left(\sqrt{A_{11}A_{22}} - A_{12} + \frac{A_{11}A_{22} - A_{12}^2}{2A_{66}} \right)} \tag{3}$$

A correction defined by Eq. (4) is then applied in order to obtain the stress concentration factor on a lug of finite width w and diameter d.

$$K_T = \left(\frac{2 + (1 - d/w)^3}{3(1 - d/w)} \right) K_{TOH}^\infty \tag{4}$$

This stress concentration factor is used along with the results of Eq. (2) to evaluate the resulting stresses in the lug that might cause the net section failure of the part for a specified in-plane load. A failure criterion should then be selected to determine if the proposed design can resist the applied loads.

During this phase, the generated laminates are categorized with respect to the Angle Minus Load (AML) parameter. This empirical method was proposed by Dorris *et al.* (1992) to estimate the properties of the laminate as a whole instead of evaluating each individual ply within the composite. For symmetric and balanced laminates that are composed of layers at the $0°$, $\pm 45°$, and $90°$ directions, the AML at the $0°$ direction is defined by Eq. (5).

$$AML_{0°} = \frac{number \ of \ \pm 45° \ layers - number \ of \ 0° \ layers}{total \ number \ of \ layers} \tag{5}$$

A quasi-isotropic laminate has an AML parameter of 25%, whereas hard laminates present a value less than 25%, and soft laminates have an AML greater than 25%. Hard laminates display a higher strength at the loading direction but are more susceptible to impact damage, which makes them inadequate for certain applications. On the other hand, soft laminates can tolerate larger strains and are usually less affected by the effect of stress concentration but tend to fail at lower loads.

2.3 Search Method

The selection of the stacking sequence is an essential stage of the design with composite materials, as it is intrinsically related to the final properties of the laminate. Furthermore, the lamination scheme can be tailored to achieve the desired mechanical behavior of the part under a particular set of loading conditions, creating an efficient structural design (Silva *et al.*, 2019). Nevertheless, this process often involves a large number of variables and so demands a significant effort during the development of the component.

Optimization techniques have been extensively researched to solve this problem. Among the proposed methods, genetic algorithms emerge as a well-suited approach to search for solutions in discrete design spaces such as those that define the stacking sequence of a composite material (Almeida and Awruch, 2009). These algorithms mimic the behavior of natural selection to find the individuals that are best fitted to an environment, which is computationally defined by an objective function that comprises the analysis of the problem and its constraints.

Considering the stacking sequence as the design variable for the optimization, the semi-analytical model described in the previous section was used to create an objective function to evaluate the fitness of a given laminate with respect to other designs. Additional constraints were also included in this objective function, such as geometric and manufacturing restrictions. This analysis procedure was implemented in Matlab, using the genetic algorithm of the optimization library available in the software. An elitist selection scheme was chosen to improve the performance of the optimization by preserving good designs throughout the generations, which promoted a more efficient exploration of the design space (Soremekun *et al.*, 2001).

3. FINITE ELEMENT SIMULATIONS

3.1 Finite Element Model

The finite element method was used to analyze the solutions obtained during the preliminary design phase in more detail. Figure (3) illustrates the relations between the individual analysis modules used in this procedure.

The model was implemented into Abaqus, and solid elements were chosen to capture the complete state of stresses in the lay-up and thus also obtain a better representation of the interlaminar stresses. The lug was partitioned in such a way to obtain a structured mesh using linear brick elements, with eight nodes, reduced integration, and hourglass control. Whenever possible, the symmetries of the part were used to reduce the size of the domain required for the simulation. Moreover, since the bending effects were negligible for all the load cases considered in this analysis, only one element was used in the thickness of each layer.
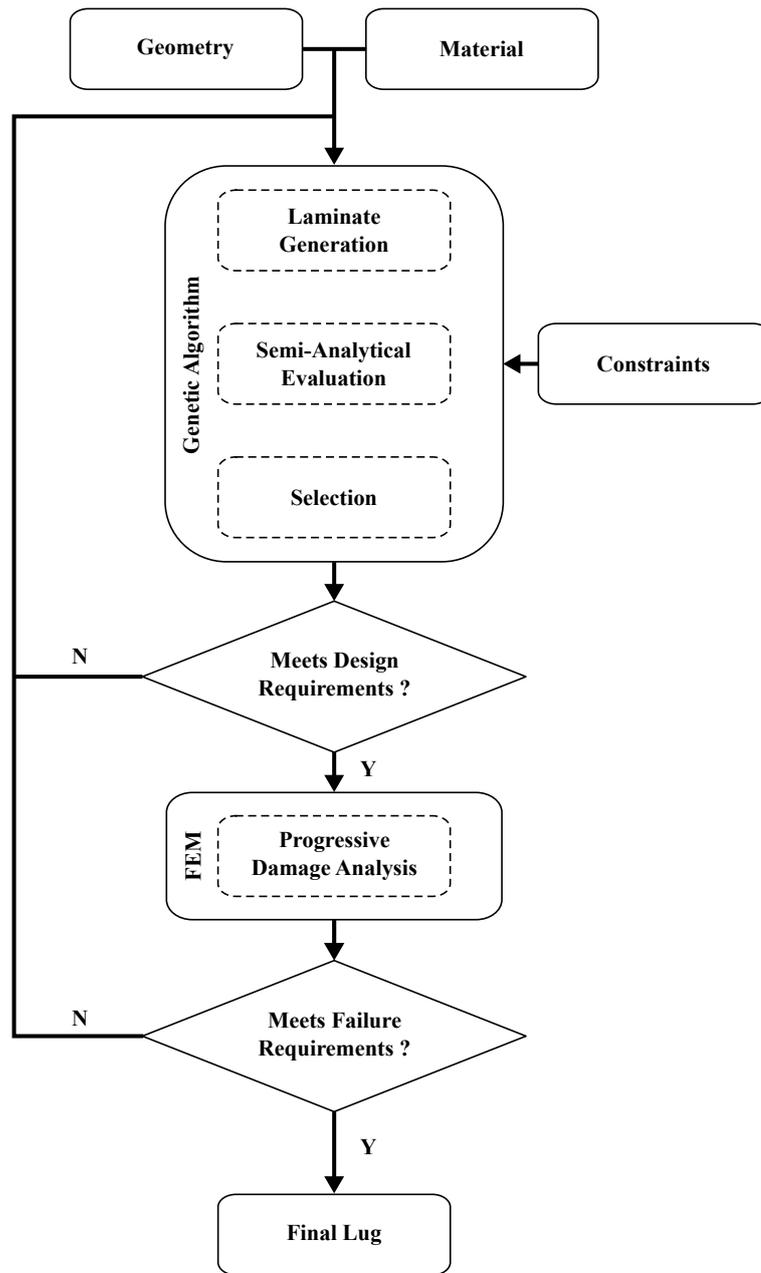
Figure 3. Overview of the design procedure.

In a conservative approach, an analytical rigid surface was used to represent the pin that applied the loads to the lug. The interaction between the lug and the pin was defined by a general contact model based on applying kinematic constraints to the surfaces in contact.

The simulation was carried out using an explicit dynamics procedure in which the state of the model was calculated at incremental time steps. In addition, the loading definition considered quasi-static conditions in order to prevent the development of inertial effects.

3.2 Progressive Damage

The progressive damage model used for these analyses was based on the failure criteria proposed by Chang and Chang (1987). This model determines the type of damage inflicted to the part, the residual strength of the structure, and the maximum load it can tolerate before failure.

This procedure was implemented as a user-defined material model in Abaqus/Explicit to predict the failure of solid elements during the finite element analysis (Donadon *et al.*, 2020). To avoid numerical instabilities related to the sudden change of the stresses in the regions where failure occurs, a degradation algorithm was used to gradually decrease the

material properties to zero during a predetermined time period when one of the failure mechanisms was activated. The analysis can identify fiber, matrix, and delamination failure modes. Each of these modes is represented by a corresponding failure index that is used to update the stresses obtained by the finite element model. The nodal forces and displacements are later computed using the degraded stresses determined by this process.

It was assumed that the shear stress-strain relationship of the composite material is non-linear, as described by Hahn and Tsai (1973).

$$2\epsilon_{12} = \frac{1}{G_{12}}\tau_{12} + \alpha_s\tau_{12}^3 \tag{6}$$

Where G_{12} is the shear modulus of the layer and α_s is a parameter determined experimentally. The parameter $\bar{\tau}$ is the ratio of the shear strain to the shear strength, expressed as:

$$\bar{\tau} = \frac{\frac{\tau_{12}^2}{2G_{12}} + \frac{3\alpha_s\tau_{12}^4}{4}}{\frac{S_{12}^2}{2G_{12}} + \frac{3\alpha_s S_{12}^4}{4}} \tag{7}$$

With S_{12} being the shear strength of the material. Based on these definitions, the failure index for fiber failure in tension is then calculated as:

$$e_f^t = \left(\frac{\sigma_{11}}{S_{11}}\right)^2 + \bar{\tau} - 1 \tag{8}$$

Where S_{11} is the longitudinal tensile strength of the composite material. Similarly, for fiber failure in compression:

$$e_f^c = \frac{|\sigma_{11}|}{S_{11}} - 1 \tag{9}$$

And for tensile matrix cracking:

$$e_m^t = \left(\frac{\sigma_{22}}{S_{22}}\right)^2 + \bar{\tau} - 1 \tag{10}$$

Where S_{22} is the transverse tensile strength. Matrix crushing is given by the expression:

$$e_m^c = \left(\frac{\sigma_{22}}{S_{22}}\right)^2 + \left[\left(\frac{C_{22}}{2S_{12}}\right)^2 - 1\right]\frac{\sigma_{22}}{C_{22}} + \bar{\tau} - 1 \tag{11}$$

With C_{22} representing the transverse compressive strength of the material. Finally, the failure index of delamination is defined as:

$$e_d = \left(\frac{\sigma_{33}}{S_{33}}\right)^2 + \left(\frac{\sigma_{23}}{S_{23}}\right)^2 + \left(\frac{\sigma_{31}}{S_{31}}\right)^2 - 1 \tag{12}$$

Where S_{33}, S_{23}, and S_{31} are the interlaminar tensile strengths associated with modes I, II, and III of delamination, respectively.

4. NUMERICAL RESULTS

4.1 Model Verification

The models used for the analyses of the lugs were verified against results available in the literature to identify possible issues related to their implementation. Kassapoglou and Townsend (2003) published experimental data about the failure of composite lugs loaded in tension. The tested specimens were manufactured with a quasi-isotropic laminate of unidirectional IM7/8552 tape and were similar to the model shown in Fig. (2), presenting a thickness t of 9.75 mm, a width w of 50.8 mm, a hole diameter d of 25.4 mm, and a total length l of 190 mm. Table (1) shows a comparison between the failure loads predicted with the semi-analytical model, the progressive damage simulation, and the test results.

Table 1. Comparison between the predicted and experimental results of quasi-isotropic lugs.

	Analytical Model	Progressive Damage Model	Test Results
Failure Load [kN]	90.9	94.7	97.7

The load-displacement curve of the lug, presented in Fig. (5), indicates an almost linear behavior that is in agreement with experiments using carbon-fiber-reinforced plastics. Damage was initiated on the edge of the hole in the region where stress concentration occurs. The first ply failure (FPF) happened at a load of 45 kN and was caused by matrix cracking. However, it did not immediately affect the load-carrying capacity of the laminate since it is primarily dependent on the strength of the fibers. The layers oriented at 90° were the first to fail, which is associated with the reduced strength of the material in this direction. Nonetheless, the propagation of the damage to the adjacent layers as the applied load was incremented ultimately resulted in fiber breakage, leading to the net section failure of the specimen at a load of 94.7 kN, a result that underestimates by 3% the failure load observed during the tests. The tension failure mode of the lug is illustrated in Fig. (4).
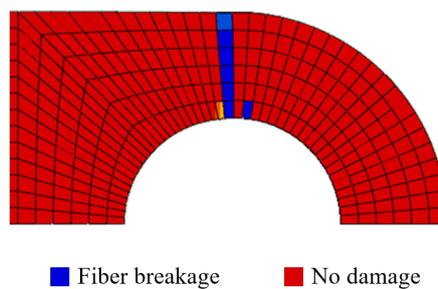

■ Fiber breakage   ■ No damage

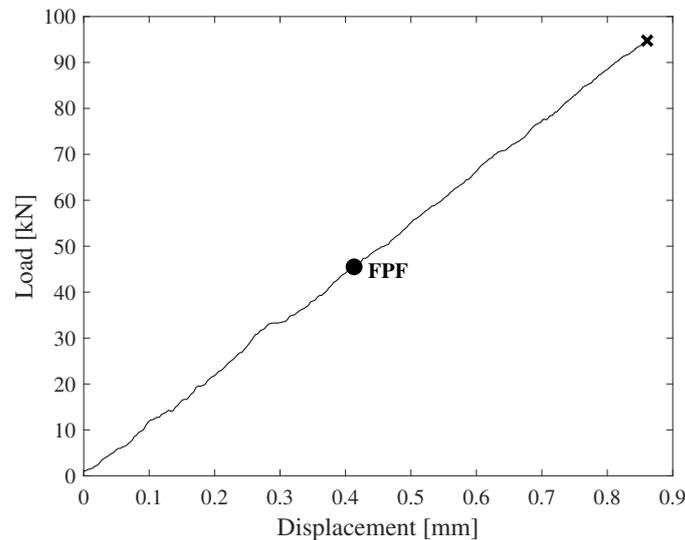Figure 4. Tension failure of the lug identified with the FEM model.

Figure 5. Load-displacement curve of the quasi-isotropic lug.

4.2 Case Study

This methodology was applied to the design of a carbon-fiber brace for a benchmark commercial aircraft, presented in Fig. (6). This brace contained lugs at its extremities that were connected to other components of the landing gear, so the length L of 760 mm, the thickness t of 50 mm, and the lug diameter d of 71.5 mm could not be modified. It was required that this brace should resist a design load equivalent to 785 kN both in tension and compression while subjected to the above indicated geometric interface constraints of the landing gear. A design philosophy was adopted for this component
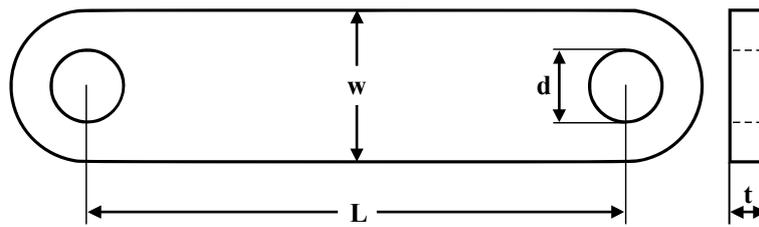
Figure 6. Landing gear brace.

where no damage was accepted at the design load. Additionally, manufacturing restrictions were also imposed on the design.

1. Only layers at the directions $0°$, $\pm45°$, and $90°$ were accepted for the stacking sequence;

2. The laminate should be symmetric, so the layers should be arranged with symmetry about the mid-surface;

3. The laminate should be balanced, with the same number of layers at $+\theta$ and $-\theta$ directions;

4. The AML of the laminate should be between -10% (very hard) and 70% (very soft);

5. There should be no sequence of more than three consecutive layers in the same orientation to reduce the propagation of interlaminar cracks.

Considering the high longitudinal loads applied to the component, the material selection was based on the requirement for high stiffness and strength both in tension and compression conditions. This motivated the choice of IM7/8552 unidirectional carbon fiber tape for the analyses, which has properties well documented in the literature (Marlett et $al.$, 2011), as summarized in Tab. (2).

Table 2. Hexcel IM7/8552 Unidirectional Tape Properties.

Property	Value
Longitudinal Tensile Modulus, E_1 [GPa]	152
Transverse Tensile Modulus, E_2 [GPa]	9.3
In-Plane Shear Modulus, G_{12} [GPa]	3.5
Major Poisson's Ratio, ν_{12}	0.316
Longitudinal Ultimate Tensile Strength, S_{11} [MPa]	2558
Longitudinal Ultimate Compressive Strength, C_{11} [MPa]	1731
Transverse Ultimate Tensile Strength, S_{22} [MPa]	64
Transverse Ultimate Compressive Strength, C_{22} [MPa]	286
In-Plane Shear Strength, S_{12} [MPa]	91
Interlaminar tensile strength of mode I delamination, S_{33} [MPa]	60
Interlaminar tensile strength of mode II delamination, S_{23} [MPa]	120
Interlaminar tensile strength of mode III delamination, S_{31} [MPa]	120
Cured Ply Thickness [mm]	0.183

The analyses performed with the genetic algorithm revealed that a hard laminate was required for this brace, as the stress concentration around the edge of the lugs caused the layers oriented transversely with respect to the load to fail at this region if not sufficiently supported by layers in the other directions, similarly to what was observed in the verification model. For this reason, the best-evaluated candidate during the preliminary design phase was a hard laminate with a stacking sequence containing 272 layers in order to resist the required tension load, of which 43% were oriented at the $0°$ direction, 47% at the $\pm45°$ direction, and 10% at the $90°$ direction, corresponding to an $AML_{0°}$ of 4%.

Additionally, the semi-analytical model was used to investigate the design space and identify a suitable width for the brace. Figure (7) shows the range of values that provided enough strength to resist the design load when evaluated with the Tsai-Hill failure criterion and that also respected the geometric interface constraints of the landing gear.

The selected laminate was then used in the finite element model of the brace. Tension was the most critical loading condition, and the results of the simulation of this case are shown in Fig. (8). The progressive damage model confirmed the presence of a stress concentration region in the lug and identified that the first ply failure mechanism to appear in this
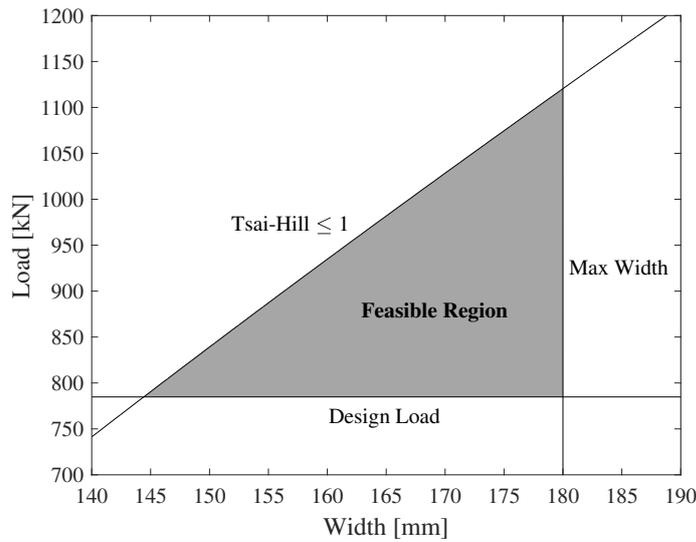
Figure 7. Analysis of the viable widths of the brace using the semi-analytical model for tension loads.

location was matrix cracking. However, the initial damage mechanisms were activated at loads significantly lower than the failure predicted with the analytical model. For this reason, the width of the lugs was increased until the maximum allowed value of 180 mm, resulting in the initiation of damage at a load of 790 kN and therefore respecting the design philosophy of the project. Furthermore, the model predicted the propagation of the damage through the part until that the development of fiber breakage caused the tension failure of the lug at a load of 1190 kN, which is in agreement with the analytical prediction and validated the preliminary design of the component.
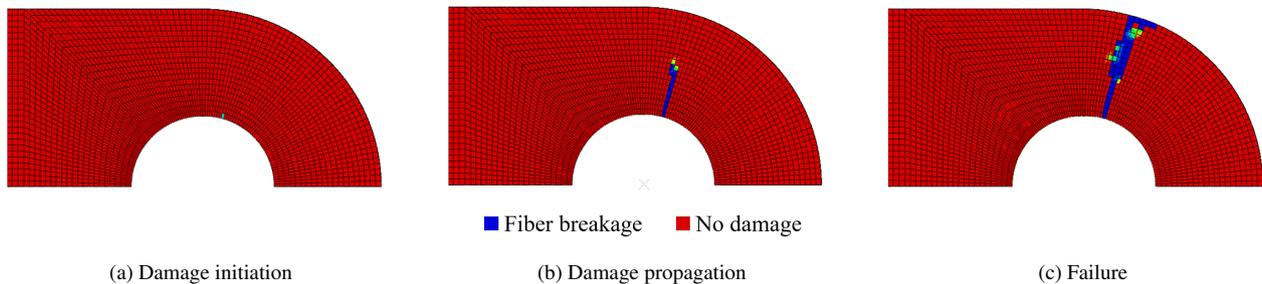

| (a) Damage initiation | (b) Damage propagation | (c) Failure |

Figure 8. Simulation results of the lug of the landing gear brace under tension load.

5. CONCLUSION

The proposed procedure for designing and analyzing lugs manufactured with composite materials includes the characterization of the propagation of damage in the component when subjected to static loads. This approach offers a tool to predict the failure loads and modes of the part since the initial stages of the design, which may improve the maturity of the project before the testing and certification phases. The progressive damage model used in the simulations can identify fiber tensile and compressive failure, matrix cracking and crushing, and delamination. Experimental tests of the examined loading conditions will be the next step in order to verify the methodology. Further work may extend the capabilities of the tool by including the analyses of oblique and transversal loads. Buckling analyses of the complete brace mechanism, impact analyses, and tests must also complement the process to fulfill the qualification requirements for the lug.

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