Fatigue life investigation on wind blades

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ABSTRACT. *Mechanical behaviour of wind blades made in composite materials has been investigate through a F.E.M. approach simulating a stress analysis over blade components. Nowadays, use of composite materials appear as wide in mechanical as well as in more field of engineering design since composite properties brings to wide and different applications due to their lightness, resistance and stress capacity. The composite materials used in wind blades appear really diffused but the peculiar mechanical framework needs a deep investigation about partial structural integrity as full. In this paper a simulation analysis by finite element code, over a concise wind blade part, has been performed showing, in the first step, the constitutive behaviour under classic load conditions, then developing a deep analysis under cyclic loads joint to thermal and chemical actions, so that a clear framework of the fatigue life can be characterized.*

RÉSUMÉ. *Le comportement mécanique des pales éoliennes fabriquées en matériaux composites a été étudié par la méthode des éléments finis (MEF) simulant une analyse de contrainte sur les composants de la pale. De nos jours, l'utilisation de matériaux composites apparaît aussi large en conception mécanique que dans plus de domaines de la conception technique puisque les propriétés des composites apportent des applications larges et différentes en raison de leur légèreté, de leur résistance et de leur capacité à résister à la contrainte. Les matériaux composites utilisés dans les pales éoliennes semblent très répandues, mais le cadre mécanique particulier nécessite une étude approfondie sur l'intégrité structurelle partielle comme complète. Dans cet article, une analyse de simulation par code d'éléments finis sur une partie concise des pales éoliennes a été réalisée, montrant dans un premier temps le comportement constitutif dans des conditions de charge classiques, puis développant une analyse approfondie sous charges cycliques conjointement aux actions thermiques et chimiques , afin qu'un cadre clair de la durée de vie puisse être caractérisé.*

KEYWORDS: *composite materials, wind blades damaging, fatigue failure.*

MOTS-CLÉS: *matériaux composites, pales éoliennes endommageant, rupture par fatigue.*

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1. Introduction

One of the biggest trends in XXI century economy is the exploitation of renewable energy sources to supply modern life demand of power. Among different kinds of alternative sources, the most important ones are the Sun and the wind. Wind energy is one of the most abundant renewable energy source on Earth and it has been used for millennia. Originally, it was used as mechanical energy source for sailing then to grind wheat through windmills. Modern wind turbines are used to produce electrical energy converting kinetic energy from the wind into mechanical energy and finally into electrical power. There are two main kinds of wind turbines: HAWT (Horizontal Axis Wind Turbines) and VAWT (Vertical Axis Wind Turbines), they differ each other for supplied power and in mechanical management.

Horizontal Axis Wind Turbines (Ashwill & Paquette, 2006) are the most common and the ones that gained the major interest in academic world mainly because of their high-power production. Scientific Research and development of new materials with high strength/weight ratio have brought to structural improvements of all the components of the energy production system: from the wind blade to the electrical components.

Among these components, central role of the electrical system is the wind blade and academic Research in the last decades pointed at its improvement in terms of reliability during its life application, which is usually between 20 and 30 years. Obviously, wind blades are subject to mechanical stresses and adverse weather conditions that can damage the mechanical properties of this component. (Brondsted, 2011)

In this paper the mechanical stresses acting on the wind blade have been analyzed (Griffin, 2004), these ones can be briefly divided into aero-dynamical forces, inertial forces and gravity force. Finite element analysis through COMSOL Multiphysics software has been carried out in order to evaluate these mechanical stresses.

2. Composite mechanics

Composite materials (also called composition materials or shortened to composites) are materials made from two or more constituent materials with significantly different physical or chemical properties, that when combined, produce a material with different characteristics from the individual components.

In a composite material, the different components remain separate and can be distinct within the finished structure.

The new material may be preferred for various reasons, such as: lightness, strength or better application for the considered purpose.

Generally speaking, a composite material is made up of:

1. Matrix: (normally a form of resin) that keeps the reinforcement in the desired orientation. It protects the reinforcement from chemical and environmental attack, and it bonds the reinforcement so that applied loads can be effectively transferred.

2. Reinforcement: made up of fibers and used to fortify the matrix in terms of strength and stiffness. The reinforcement fibers can be cut and placed in different ways to affect the properties of the resulting composite.

3. Interface: part of a composite material between reinforcement and the matrix

If fibers are mutually parallel in the matrix, we have unidirectional composites and material mechanical characteristics are anisotropic: this feature (typical of composites) is very important because of the possibility to design and build a particular type of material in function of structural needs.

In fact, materials with desired mechanical characteristics can be built using layers with mutual parallel fibers and overlapping different layers with different orientations. In this case the single layer is defined as lamina and the union of laminas is called laminated. Traditional materials can be considered as homogeneous (with uniform proprieties, independently from position) and isotropic (with constant proprieties in every direction and in every part) materials.

On the contrary, composites are usually heterogeneous and anisotropic but in the paper, we will to consider it, thermodynamically speaking, as homogenous. They can be analyzed from the micro- and macro- mechanics points of view.

Micromechanics analyzes composites in order to determine elastic modules starting from those of the single components. However, the micromechanical analysis has some limitation because they assumes a perfect fitting between fibers and matrix, which is not always satisfied. For this reason, proprieties known by the micromechanical approach are better than real ones.

This analysis can be applied on the design of a single lamina made up of a matrix and a bundle of mutual parallel fibers.

This kind of laminas are not sufficient for engineering use because they have very low resistance and strength, for this reason industry uses laminates. Laminated composites are made up of several laminas stuck together, each of which has different-oriented fibers, so that they have higher values of resistance and strength. Macro-mechanics is the study of laminated composites, analyzed as composition of macroscopic behavior of the single constituent laminas. Through the "lamination's theory" we can know elastic constants of the single laminas and of the entire laminate.

2.1. Micromechanics

It must be pointed out that micromechanics models are still only approximate models of the behavior of composite materials. This begins with the approximation used for the geometry. It is practically impossible to use a model based on the actual spatial distribution of the reinforcing material within the specific composite that may be used in a design. Instead, two approaches are commonly used to arrive at an approximation for the geometry. The first of these is the use of a statistical distribution for the fiber within the matrix material. The fiber spacing is hence a random variable. In the other geometry approximation, a periodic structure is assumed in which the fiber is evenly spaced throughout the matrix continuum. This approach is generally simpler and allows the analysis of a single unit cell of the material. The use of a periodic distribution is typically justified when the volume fraction of fibers is high. Throughout the years, many different micromechanical models have been proposed for example the Voight model, Reuss model, Hill self-consistent scheme, Cells method, Temply-Dvorak homogenization model.

2.2. Macromechanics

Macromechanics studies laminates behavior, made up of two or more laminas perfectly fitted so that they can be considered as a single structural homogeneous element. Laminate composites strength is calculated using processes that are function of: multitude, type and orientation of laminas (with h as total thickness).

In order to apply the macro-mechanical approach some assumptions are necessary:

-Laminas which made up the laminate composite are perfectly stuck together, so that no reciprocal motion exists once subjected to external loads (motion and strain continuity in the interface of two adjacent laminas);

-A segment normal to the horizontal plane of the laminate, stays normal to that plane even after any strain, so that $\gamma xz = \gamma yz = 0$;

-Strain on z direction is negligible in comparison to the ones in x and y directions;

-Laminate thickness is small in comparison to the other two dimensions.

These hypotheses represent the framework of the “Laminate Theory”. Specific loads and moments (per unit of width) are equal to integrals, on the total laminate thickness h, of stresses and of moments acting on the laminas

$$N_x = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_x \, dz \; ; N_y = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_y \, dz ; T_{xy} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \tau_{xy} \, dz \qquad (1)$$

$$M_x = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_x z \, dz \; ; M_y = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_y \, z dz ; M_{xy} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \tau_{xy} z \, dz \qquad (2)$$

The following equations, represents the constitutive equation of a laminate:

$$\begin{Bmatrix} N_i \\ M_i \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon_i \\ k_i \end{Bmatrix} \qquad (3)$$

In formula (3), N_i and M_i representing the generic stress and moments fields, A and B, represents the bending and tensile stiffness matrix, while matrix D is function of tension and bending properties of laminate and finally ε_i, k_i are axial, shear and flexure components of the strain field. Through the last constitutive equation, we can know the six components of strain using third order matrices.

3. THERMOMECHANICS AND FATIGUE

3.1. Theoretical Termomechanics

In this paragraph we will able to represent some fundamental questions about the relationship among thermal load and composite materials, since the temperature gradient result as uniformly applied over any blade (Landers *et al.*, 2017). Generally composite materials are thermally anisotropic and inhomogeneous (Rolfes & Rohwer, 2000) since the conductivities of fibers and matrix appear as dissimilar meaningfully. In thin-walled composite the transverse temperature distribution can be approximate by a linear as well as quadratic function and this assumption is the thermal laminate theory framework. Here we will to remark as follow: 1- the thermal conductivity in the thickness directional is equal on all layers. 2- Heat transfer resistance at interface is neglecting. 3- The temperature distribution in the thickness laminate may be expressed as linear function. Neglecting transverse stress and strain the constitutive equation for laminate composite can be written in short form. (Kant & Babu, 2000)

$$\sigma = K(\varepsilon - \varepsilon_t) \tag{4}$$

where:

$$\begin{aligned} \sigma &= \{\sigma_x \sigma_y \tau_{xy} \tau_{yz} \tau_{xz}\}^{\mathrm{T}} \\ \varepsilon &= \{\varepsilon_x \varepsilon_y \gamma_{xy} \gamma_{yz} \gamma_{xz}\}^{\mathrm{T}} \\ \varepsilon_t &= \{\alpha_x, \alpha_y, \alpha_{xy}, 0\}^{\mathrm{T}} \Delta T \end{aligned} \tag{5}$$

in the formulas (4 & 5) σ, ε and ε_t are respectively the stress field, the total strain and the thermal strain vector while the K matrix represent the stiffness properties to the laminate, α_{ij} coefficients depending from the lamina thermal expansion coefficients and finally T the temperature rise. So, the thermal equilibrium problem can be placed as follow thorough the energy functional

$$\Pi = \frac{1}{2} \int \{\varepsilon_0 - \varepsilon_t\}^T \sigma \, dv + \int \varepsilon_l^T \sigma \, dv \tag{6}$$

where ε_0 and ε_l respectively represent the linear and non-linear parts of the strain tensor. After some substitution we find the final stress resultant as.

$$\bar{\sigma} = D\bar{\varepsilon} - \sigma_t^* \tag{7}$$

In the formula (7)

$$\bar{\sigma} = \{N^T M^T K^T\}^T \;\; and \;\; \sigma_t^* = \{N_t^T M_t^T O_t^T\}^T \tag{8}$$

The two vectors represent respectively the stress component in single as coupled form, while the element of the matrix:

$$D = \begin{bmatrix} D_m & D_c & 0 \\ D_c^T & D_b & 0 \\ 0 & 0 & D_s \end{bmatrix} \tag{9}$$

D_m, D_b, D_c, and D_s are the membrane, flexural, membrane-flexure coupling and shear rigidity matrices respectively. All this following the standard procedure bring us to the numerical implementation by F.E.M. code. (Battacharya *et al.*, 2017)

3.1.2. Fatigue load

A coupled investigation about the paragraph argument has been developed in (Li, 2018) where the author has been investigating about damage and fracture of long fiber reinforced ceramic matrix composites subjected to the isothermal cyclic fatigue. Here, we report some ideas according to this topic but our track is going towards different questions. As general framework two type of fatigue load may be identified: the first one as cyclic and the second one as dwell fatigue. Here we prefer to consider the first but even the second type is not negligible since the dwell action can be applied regularly on the blade regime. On this approach we consider the microscale framework and so an RVE has been defined considering two individual laminas. Our attention is focused on the breaking fiber / matrix or better delamination phenomenon. The delamination may be assessed with reference to an elementary model which leads to the union of two surfaces connected by an interface modelled as a continuous and uniform springs distribution of adequate rigidity (k = 3x104 N/mm^2). The detachment can be evaluated with reference to a basic model using a cohesive damage model such that the defects diffusion can be predicted. Here we use a 16-node iso-parametric element with thin thickness (less 1/100 respect to the laminate) and a bilinear constitutive law. Regarding the damaging, over the cross laminates composite under cyclic loads, the crack number over the surface growth as linear relationship versus the cyclic number, while initially growth over the longitudinal laminas and after having a plateau then increasing until the failures. About the residual strength a main parameter is the defect density, habitually the medium step among the crack. The follow figure clarifies this assumption.

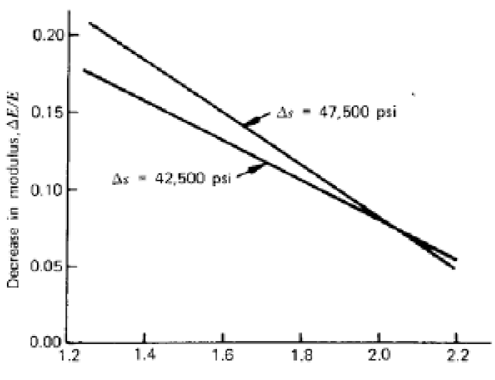

Figure 1. Stiffness step crack/thickness relationship

About to model the delamination phenomenon the follow consideration has been developed (Buonsanti, 2018). Inserting between two adjacent laminas the interface element the displacement and strain components follow:

$$u = \begin{Bmatrix} u \\ v \\ w \end{Bmatrix}; \quad \begin{Bmatrix} \gamma_s \\ \gamma_s \\ E_n \end{Bmatrix} = \begin{Bmatrix} u_{s,n} + u_{n,s} \\ u_{t,n} + u_{n,t} \\ u_{n,n} \end{Bmatrix} \tag{10}$$

With the position:

$$E_m = \sqrt[2]{< E_n^2 > + \gamma_{sn}^2 + \gamma_{tn}^2} \tag{11}$$

Following the proposed constitutive law we say: 1- When the true deformation is less respect to E_m^0 material having a linear behaviour and then no damage is developed. 2- When the true strain is equal to E_m^0 the interlaminar damage starting then, the interface stress is linearly decreasing. 3- The strain component E_m^f regard the total damage namely, done the whole detachment. After some calculation (Buonsanti, 2018) we obtain

the damaged laminate constitutive equation:

$$\sigma = DE \tag{12}$$

where the constitutive matrix *D* chance as:

$$D = \begin{cases} KI & \alpha \leq E_m^0 \\ (1-d)KI + dK_c & E_m^0 < \alpha < E_m^f \\ KI_c & E_m^f \leq \alpha \end{cases} \tag{13}$$

in the formula (13) *K* represent the reduced stiffness, *I* the identity matrix, *d* a damage parameter and I_c to avoid penetration of the laminate surfaces since damaged zones represent stiffness reduced.

4. Modeling and simulation

4.1. Blade element model

Betz's theory is limited because maximum exploiting power is not linked to the features of the element, which extract it, the turbine. The blade element theory resolve this question, allowing us to calculate the radial distribution of a (induction factor) once given the aerodynamic coefficients (lift and drag) of the considered blade profile. Momentum theory, in fact, does not provide enough equations to solve to evaluate the differential propeller thrust and torque at a given span location, unless steady state flow is assumed. Adding other equations related to the characteristics of blades (such as airfoil shape and twist distribution) resolve these problems. (Ike, 2018). Blade element (BE) theory employs these geometrical properties to define the forces exerted by a propeller on the wind.

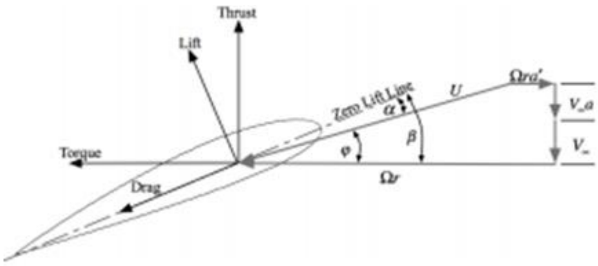

Figure 2. Blade element and aerodynamical force

Blade element theory involves splitting the blade up into N elements, each of width *dr*. For each element, a differential propeller thrust, $d\Lambda$, and torque, dQ, can be assigned. For simplification, some assumptions follow:

-There is no interaction between each blade element;

-The forces on the blade are exclusively produced by the two-dimensional lift and drag parameters of the blade element, with orientation relative to the incoming flow.

-In order to determine the aerodynamic forces on the blade element, we need the angle of attack. Geometrically we can derive U (resultant velocity at blade element) as:

$$U = \frac{V_\infty(1+a)}{sin\varphi} \tag{14}$$

In the formula (14) V_∞ is the free-stream speed, while a is the axial induction factor. From these equations, BE theory can calculate the thrust and the torque for each section as:

$$d\Lambda = \frac{1}{2}B\rho U^2(C_L\, cos\varphi - C_D sin\varphi)cdr \tag{15}$$

$$dQ = \frac{1}{2}BpU^2(C_L sin\varphi + C_D cos\varphi)crdr \tag{16}$$

With, c chord length, dr blade element and annulus width

C_D drag coefficient, r radial position, C_L lift coefficient, B number of blades. Combining the results of the previous two theories, a new more complete model is introduced namely, the blade element momentum theory (known as BEM-theory).

This approach is based on the differential blade thrust, $d\Lambda$, and torque dQ, derived from both momentum theory and blade element theory. (Ike, 2018) The effect on induced speed in the propeller plane varies throughout the blade. The previous BEM theory does not consider the influence of vortices shed from the blade tips into the slip - stream on the induced velocity field.

In order to improve the theory, a new factor F originally developed by Prandtl has to be introduced. This factor takes into account the suction effect made by the blade so that air tends to flow over the blade tip from the lower surface to the upper one, reducing the resulting forces next to the tip.

$$F = \frac{2}{\pi} cos^{-1} e^{-f} \ ; \ f = \frac{B}{2}\frac{R-r}{rsin\varphi} \tag{17}$$

Consequently, formulas (15) and (16) assume the form:

$$d\Lambda = 4\pi\rho V_{\infty}^{2}(1+a)aFdr \tag{18}$$

$$dQ = 4\pi\rho V_{\infty}^{2}(1+a)a'Fdr \tag{19}$$

Considering lift and drag coefficients as function of the angle of attack, for each blade and then we obtain a final equations set that may be solved deducting velocities and forces on each blade element. Over the blade element set, the thermal load conditions regards two different values, the first one on the external side at high value, or the sun effects and the second one, over the inner side not sun light up, at environmental temperature. This formulate temperature gradient arrange the thermal load and so consequently the thermal effects can be deducted in the computational phase.

5. Numerical simulation

5.1. Results

In this section we report the simulation results after the numerical implementation made by Comsol code up-graded by specific MatLab code routine. A first simulation at macroscale has regarded a blade portion under pressure and temperature loads conditions, while in a second step, tied to the first, the simulation has been applied over the simple RVE (representative volume element) namely over two laminas submitted to possible delamination. This RVE has been selected between the stress maps surface, finding the main point where stress becomes critical. In this way the possible damaging and cracking forces may be ready to amplify their geometric consistent growing until the complete material failure. Clearly, all the consideration on the blade element report the uncertainty respect to the complete blade behavior but for us this represents a first approach to the question. Future issues covering the previous specify.

5.1.1. Macroscale simulation results

In this section we report the main results about the numerical simulation marked in two steps namely, the first one over the blade element as follow:

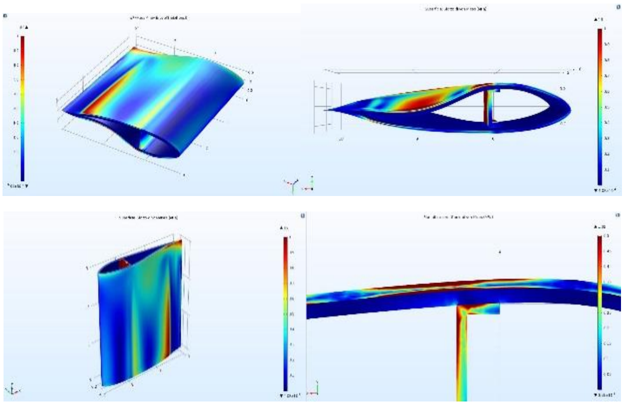

Figure 3. Von Mises stress coupled T = -5°C

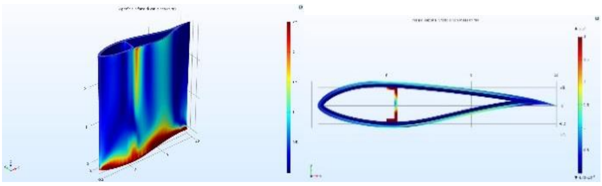

Figure 4. Von Mises stress coupled T = 60°C

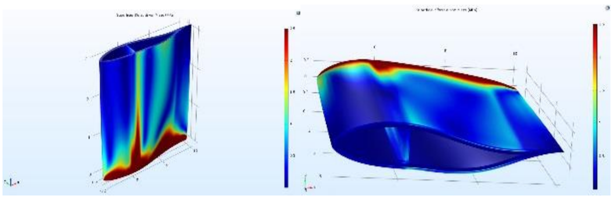

Figure 5. Displacement field coupled T= -5°C

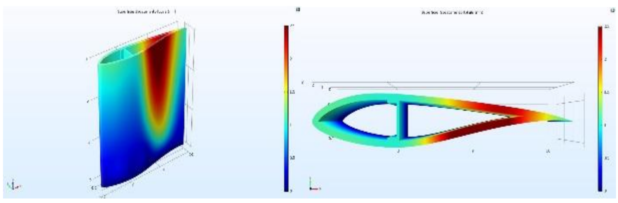

Figure 6. Displacement field coupled T = 60°C

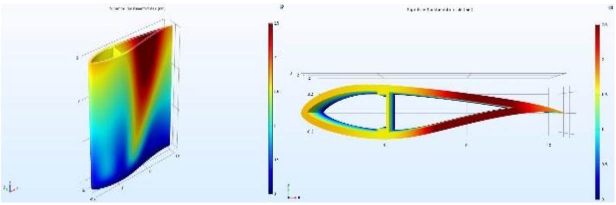

Figure 7. Total displacement field

5.1.2. Microscale simulation results

In this section the simulation results about the RVE select are reported. The research brings us to focus the stress point which values appear as greatest. Delamination phenomenon is the target of our simulation, since this damaging represent the major of the critical conditions which composite materials should be revisited. Here we represent two load conditions, the first one only surface pressure and the second one pressure together thermal conditions.

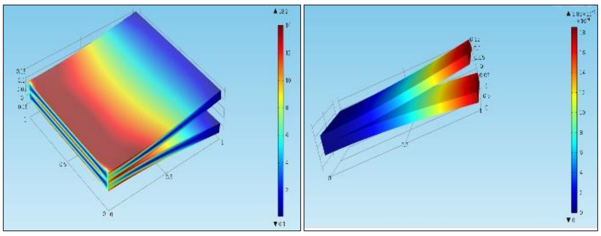

Figure 8. Von Mises and displacement field (RVE)

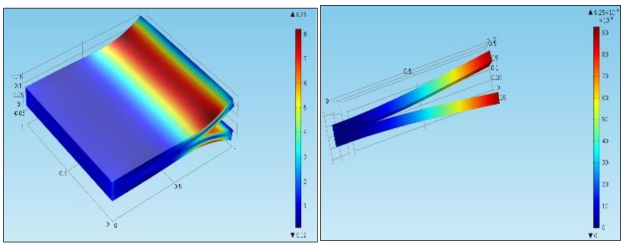

Figure 9. Von Mises & displacement field thermo coupled

6. Conclusion

A first investigation about damaging in blade composite laminates has been developed starting from simple consideration regarding a specific blade portion undergoing typical operative loads. Among others we considered: aerodynamic loads joint to the thermal response. In fact, wind blades suffer high temperature gradient throughout their side by the Sun.

These loads conditions represent possible origin to the critical phase especially when continuously the composite is submitted to cyclic loads.

The developed paper has investigated two different aspects of blades mechanic: the first one with a macroscale approach by FEM implementation over a meshed blade portion; the second one, from the macroscale base, where we extract a RVE, which boundary conditions derive by macroscale results. Following on RVE we perform a new numerical implementation, finding the delamination evolution steps under different load conditions. The results appear in good agreement with damaged laminate composites and experimental results in literature.

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