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Progressive damage in composite bolted joints via a computational micromechanical approach

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ABSTRACT

In this paper, the pin-induced progressive damage of fiber-reinforced laminates employed in composite bolted joints is addressed. A nonlinear finite-element computational approach is developed, by describing the pin-based load transfer mechanisms via an incremental formulation that accounts for the unilateral contact between pin and laminate. The nonlinear incremental damage problem is faced via a multiscale strategy that couples: the laminate theory; the micromechanical bridging model for describing stress localization at the constituent scale within each ply comprising the laminate; a microscale biaxial strength criterion combined with a local material degradation rule. Some illustrative numerical applications are presented and discussed, highlighting the good agreement of the proposed results with available benchmarking experimental evidence, as well as providing quantitative indications on the influence of some model parameters.

1. Introduction

In the context of innovative and advanced materials for structural use, fiber-reinforced polymers (FRPs) have attracted in the last decades a large interest of both researchers and manufacturers, resulting nowadays widely spread in many engineering fields (such as for civil, aeronautical, aerospace, industrial, automotive, naval applications). With the aim to enhance their mechanical properties, allowing for a material design increasingly oriented towards specific and challenging functional requirements, as well as in order to optimize production technology and processes, FRPs based on carbon, glass, aramid or basalt fibers have been the object of many recent studies, addressing experimental practices, theoretical modeling, and numerical analyses. Specifically referring to applications of composite polymers in civil engineering, systematic and critical reviewers can be found, for instance, in Refs. [1–3].

Since standard design methodologies developed for conventional materials are not straight applicable in the case of structural elements based on FRPs, a great effort has been recently devoted to furnish synthetic indications and practical rules, towards the definition of suitable guidelines and possible codes to be employed for structural engineering design practice. In this framework, mention can be made to the EuroComp Design Code and Handbook [4], to the EN 13706 standard [5], to some technical recommendations recently provided by the Italian National Research Council [6,7], as well as to Manuals of Practice (MOP) n. 102 proposed by the Construction Institute of the American Society of Civil Engineers (ASCE) [8].

In order to satisfy specific geometric and functional requirements, structural elements made up of composite polymers generally need to be connected. For instance, in aerospace and aeronautic domains FRP panels (namely, laminates) are suitably joined to obtain specific functional surfaces; in civil applications pultruded FRP beams or columns are connected together to realize truss structures [9–11]. Due to the possible occurrence of stress concentrations arising in connected structural systems, jointed regions surely represent critical weaker areas in FRP-based composite structures, thereby requiring a proper identification of the joint strength properties. Nevertheless, the analysis of strength features and failure modes in joined composite-based systems is not a trivial task, since loading transfer mechanisms, stress concentrations, damage initiation and propagation, are deeply associated with high anisotropy and heterogeneity induced by the material microstructure.

Composite-based structural elements are usually joined through bolted connections, adhesive binding, or by adhesive/

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bolted hybrid joints. In particular, referring to the case of laminates joined via bolted connections, failure modes under tensile loads usually occur following four different basic mechanisms, namely, cleavage, net-tension, shear-out and bearing [12], whose activation is strongly related to both geometric (e.g., bolt diameter, laminate width and thickness, end-distance) and material properties (e.g., fiber-to-load angle, matrix and fiber mechanical behaviour, laminate stacking sequence). As a matter of fact, experimental and modeling evidence has highlighted that in bolted connections of laminates characterized by large enough width and end-distance values, the dominant failure mode is generally the bearing one, with a possible influence of the net-section mode [12,13]. The former mainly consists in a local laminate compressive failure induced by the tendency of the bolt to crush the composite material along the loading direction, with the local occurrence of matrix cracks. The latter is characterized by the tensile failure of constituents located in the orthogonal direction with respect to the main loading one.

Due to the great relevance for design purposes, many studies have been carried out dealing with pin-bearing failure mechanisms in bolted laminates. In detail, several well-established experimental and numerical results can be found in the specialized literature, allowing to establish useful comparative indications on the bearing strength as a function of the fastener features (e.g., bolt diameter, pin-hole clearance) [14–16,66], of the joint geometry (e.g., plate width and thickness) [17–20], of the end-distance [17,19], of the laminate stacking sequence [19,21,22], of the mechanical properties of the composite material (e.g., matrix type and fiber nature) [23,24], of the loading direction [15,18,25], and of preloading conditions [12,26,27]. An useful overview of bearing failure mechanisms in bolted connections for composite structural elements, supplied in a technical context and oriented towards a critical analysis of the current design practice, can be found in Refs. [28,29]. Moreover, the mechanical response of multi-bolted composite laminates has been recently addressed, via both experiments and numerical simulations, in Refs. [30–32], where a special focus is provided on the load partition features and stress distribution mechanisms induced by these type of connections.

In order to furnish useful indications towards the proper definition of suitable approaches for analysis and design of bolted joints between FRP-based structural elements, consistent modeling strategies and effective numerical methods are promising tools to support experiments in predicting failure pin-bearing mechanisms, as well as for detecting damage initiation states and progressive damage patterns. To this aim, the limit state of FRPs has to be properly described, possibly distinguishing failure states at different scales.

Several failure criteria for composite polymers, and differently accounting for micro-structural material features, are available (e.g., [42–52]). Nevertheless, at the best of the authors' knowledge, current modeling strategies and numerical approaches dealing with progressive damage in fastened composite laminates are mainly based on micro-mechanical formulations that at most account for mechanical response at the ply level (that is, at the mesoscale), without explicitly considering stress localization mechanisms in microscale constituents (namely, in fibers and matrix) [23]. In detail, many numerical studies (e.g., [33–41]) adopt mesoscale criteria such as the ones proposed by Hashin [44], Rotem [45] and Sun et al. [48], where the occurrence of fiber and/or matrix failure is not explicitly referred to any microscale stress measure (namely, at the constituents level), but is postulated by comparing the mesoscale stress field with single-ply strength features.

In this paper, in order to relate damage patterns to local stress fields at the constituents scale, the progressive pin-induced damage problem in bolted joints between FRP composite laminates is faced via an incremental nonlinear elasto-damage modeling technique, based on the micro-mechanical formulation proposed by Huang [52,53]. Accordingly, starting from a macroscale modeling of FRP laminates via a single-layer approach [54], effective estimates of average microscale stress measures at fibers and matrix level are provided in each laminate ply, by introducing suitable tangent localization linear operators. As a result and in agreement with preliminary numerical evidence [55], such an approach allows to obtain more accurate descriptions of the local damage onset, of the damage propagation patterns, and of the pin-based bearing failure load with respect to modeling strategies based on mesoscale strength criteria such as the Rotem one [45]. As a matter of fact, the capability to describe via a more accurate and comprehensive framework the stress localization at the constituent scale opens towards the possibility of a more effective design of bolted joints involving FRP-based laminates. Proposed approach, implemented via a finite-element numerical scheme and accounting also for nonlinear contact between bolt-pin and laminate, has been applied to some illustrative benchmarking cases, highlighting soundness and accuracy of the adopted modeling technique.

The paper is organized as follows. In Section 2 the problem under stake is introduced by referring to the case of a symmetric single bolted joint. Moreover, the progressive damage model is formulated via an updated-Lagrangian incremental strategy, by describing the adopted micro-mechanical approach (Section 2.1), the failure-analysis strategy (Section 2.2), and the degradation rule to be applied to constituents that experience damage (Section 2.3). The numerical implementation is based on the computational procedure detailed in Section 3. Illustrative numerical applications and comparisons with available experimental evidence are proposed and discussed in Section 4. Finally, some concluding remarks are drawn in Section 5.

2. Problem statement and progressive damage model

Let the symmetric single-bolted joint sketched in Fig. 1 be considered, the central plate-like structural element being the composite laminate sample addressed in the following. Let a global Cartesian frame be introduced, referred to the orthonormal basis $\mathscr{B} = \{\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3\}$, $\mathbf{e}_3$ being the through-the-thickness direction and $(\mathbf{e}_1, \mathbf{e}_2)$ lying on the middle surface $\mathscr{S}$ of the laminate in the reference configuration. The latter is identified by the region Ω, defined as

$$\Omega = \left\{(\mathbf{x}, z), \in, \mathbb{R}^3, :, x, =, (x_1, x_2) \in \mathscr{S} \subset \mathbb{R}^2, z \in \left[-t/2, t/2\right] \subset \mathbb{R}\right\} \tag{1}$$

where t is the laminate thickness, assumed to be small in comparison with the in-plane dimensions. Let the laminate sample be pierced through a cylindrical hole, whose axis is parallel to $\mathbf{e}_3$ and whose intersection with the plane $(\mathbf{e}_1, \mathbf{e}_2)$ identifies the internal circular portion $\partial\mathscr{S}_{in}$ (having diameter D) of the boundary of $\mathscr{S}$, such that $\partial\mathscr{S} = \partial\mathscr{S}_{in} \cup \partial\mathscr{S}_{out}$ and $\partial\mathscr{S}_{in} \cap \partial\mathscr{S}_{out} = \varnothing$, where $\partial\mathscr{S}_{out}$ is the external boundary part of the laminate middle surface. Moreover, let the hole be occupied by a cylindrical pin bolt, with diameter $d \leq D$ and whose reference cross-section $\mathscr{P}$ on $(\mathbf{e}_1, \mathbf{e}_2)$ has the boundary $\partial\mathscr{P}$ and the centroid $G_{\mathscr{P}}$, the latter being identified by the position vector $\mathbf{x}_{G\mathscr{P}}$.

The laminate is assumed to consist in K perfectly-bonded unidirectional fiber-reinforced layers Ω_k (namely, plies), with a symmetric stacking sequence and such that $\Omega = \cup_{k=1}^{K} \Omega_k$, where $\Omega_k = \{(\mathbf{x}, z) : \mathbf{x} = (x_1, x_2) \in \mathscr{S}, z \in [z_{k-1}, z_k]\}$, with $(z_k - z_{k-1}) = t_k$ the thickness of the kth ply, and with $z_K = t/2$ and $z_0 = -t/2$.

Addressing the kth ply, let a local Cartesian frame be introduced,