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Experimental design of the bearing performances of flax fiber reinforced epoxy composites by a failure map

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ABSTRACT

This paper represents the first effort aimed to the investigation of the pin/hole contact stress and failure mechanisms of epoxy composites reinforced with woven flax fabrics, underwent to tensile bearing tests. In particular, the maximum loads and failure modes are evaluated at varying the laminate geometrical configuration. In order to optimize the use of polymer composites reinforced with flax fibers in structural applications, an experimental failure map, identifying main failure modes of mechanically fastened joints, is obtained as function of hole diameter, distance of the hole from the free edge of the laminate and laminate width. Moreover, a theoretical approach based on the observation that a particular fracture mechanism occurs when its threshold fracture load is lower than the loads of the other competitive ones, is proposed. Main goal of this paper is to give a simple experimental methodology to support the joining design of natural composite laminates reinforced with woven flax fabrics.

1. Introduction

Natural fiber reinforced polymer composites are nowadays widely used in several engineering fields thanks to a good compromise between their specific mechanical properties, low raw material cost, lightweight and low environmental impact. In order to assemble these environmental friendly elements the most important methods is the adhesive and/or mechanical fastening joints.

Adhesive connections present several advantages such as reduction of local delamination due to the absence of holes, weight decrease, good fatigue resistance, high resistance to degradation phenomena due to galvanic corrosion. On the other hand, they cannot be used to obtain structures that require subsequent disassembly for maintenance, repair and inspection. Moreover, bolted joints present better tolerance to environmental effects than adhesive one as well as ensuring to transfer higher mechanical stresses among the joined structures. In this context, it is of the utmost importance for the designers to understand the failure mechanism of fastened joints because mechanical fasteners reduce the load carrying capability of the structure due to complex stress field near the hole area. Several previous works evidenced that the failure of plate-to-plate connections can occur through four basic mechanisms: i.e., bearing, net tension, shear out and cleavage [1–4]. In particular, most studies highlighted the effect of geometrical variables such as substrate thickness, substrate width to-hole diameter ratio (W/D) and distance of the hole edge from the free edge to-hole diameter ratio (E/D) on the failure mechanism [5–7].

Bearing failure occurs when the ratio W/D is high, it is characterized by failure near to the contact region at the hole edge due to compressive stresses acting on the hole boundary [8]. The bearing resistance of pin-loaded composites depends on fibre orientation, fabric architecture and stacking sequence [9,10]. This mode of failure is strongly affected by the lateral constraint that delays ply delamination, i.e. splitting between layers in the through-thickness direction. It may result in a progressive deformation with continuous localized buckling of the fibers and crushing of the matrix. Net tension failure, characterized by sudden crack propagations transversely to the load, occurs when the ratio W/D is low (i.e., when the cross section area is relatively small). It is worth noting that net tension mechanism is the dominant one in multi-row bolted joints due to the high stress concentrations in correspondence to the first row of bolts [1]. Shear out failure, which occurs when the ratio E/D is low, is mainly caused by shear stresses acting parallel to the shear stress direction in the bolt and occurs along shear out planes on the hole boundary in the principal fastener load direction. In most cases, shear out failure should be considered as a special case of bearing failure with a short distance between the hole edge and the free edge.

Moreover, in several laminates it is possible to observe a "cleavage" failure mode, which occurs when the fibers are oriented along the load

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direction and it can be considered as a mixed failure between shear out and net tension. In many cases, this failure mode is initiated at the joint end rather than adjacent to the bolt hole [11].

Among these failure modes, bearing mode is the only one that produces a progressive failure of the composite substrate thus being much less catastrophic than other low-strength and premature failure mechanisms. For this reason, in several fields such as aircraft industry, composite bolted joints must be designed (i.e., by adequately choosing of E/D and W/D ratios) in order to fail under bearing mode thus avoiding catastrophic failures. Anyway, the different constructive boundary conditions and the more limited available installation space of the automotive field lead to use thinner and more anisotropic laminates than those of aircraft one, in addition to narrow flanges. For these reasons, automotive joints fail more frequently through shear out rather than bearing [12].

The difficulties of a correct and effective design of a mechanical joint are amplified if natural fiber composite laminates are used as joining sheets. The sensitivity both to localized stresses and to drilling induced damages of this class of materials [13–15] makes particularly difficult to correctly define the geometric parameters needed for a good mechanical stability of the mechanically joined structure.

Despite several investigations have been carried out on the influence of the geometrical configuration on the failure modes and strength capability of pin-loaded fiber reinforced laminates, to the best of our knowledge very limited scientific works can be found in literature concerning fastened joined composite laminates reinforced with natural fibers [16,17]. Since these fibers are nowadays commonly used as reinforcement of polymer-based composite materials in several industrial applications [18–26], it is of upmost important to investigate their behavior in pin-loaded laminates. In this regard, the present paper is the first attempt concerning the evaluation of the bearing behavior of epoxy based laminates reinforced with flax fiber, one of the most widely used lignocellulosic fibers [27–31], thanks to its specific mechanical properties and sound absorbing efficiency [32,33].

In particular, this paper was focused on the relationship between the mechanical performances and the evolution of damage mechanisms evidenced by pin-loaded flax reinforced composites. The maximum load was considered to assess the composite laminate resistance and failure modes were evaluated at varying the hole diameter (D), the laminate width (W) and the distance between the hole center and the laminate free edge (E). Finally, the effect of joint geometrical configuration on failure mechanism was evaluated by using a failure map based on a simplified theoretical model. In this map all failure mechanisms experimentally evidenced, were clustered at varying W/D and E/D geometrical ratios, identifying well defined regions related to the typical failure mechanisms of mechanically-fastened joints.

2. Material and methods

A composite panel with dimension of 350 × 350 mm^2 and nominal thickness of 6.33 ± 0.25 mm was manufactured through vacuum assisted resin infusion technique, a close mold technique where dry plies are placed in the mold and compacted by a vacuum bag. The dry fabrics are impregnated by resin mainly driven by vacuum applied through a vacuum pump. To facilitate the resin flow during infusion, a flow mesh layer is placed over the lay-up assembly. A commercial epoxy resin SX8 EVO (Mates Italiana s.r.l., Italy) and ten laminae of 2 × 2 twill weave woven flax fabrics with nominal areal weight of 318 g/m^2 and nominal thickness of 0.3 mm (Lineo, France), were used as matrix and reinforcement, respectively. Before the cutting phase, the panel was cured at 25 °C for 24 h and post-cured at 50 °C for 8 h.

In order to evaluate the void volume fraction, the theoretical and experimental densities (i.e., ρ_t and ρ_e) of the laminate were compared as given by the following equation [34]:

$$\nu_V = \frac{\rho_t - \rho_e}{\rho_e}$$

The experimental density ρ_e was measured using a helium pycnometer Thermo Electron Corporation model Pycnomatic ATC whereas the theoretical density ρ_t was calculated as following:

$$\rho_t = \frac{1}{\left(\frac{W_f}{\rho_f}\right) + \left(\frac{W_m}{\rho_m}\right)}$$

where ρ_m, ρ_f, w_m and w_f represent the densities and the weight contents of epoxy matrix and flax fiber, respectively. Ten measurements were performed and the average value was then recorded. It was found that the flax laminate shows fiber and void volume fractions equal to 33.4 ± 0.3% and 1.3 ± 0.1%, respectively.

Specimens having length 150 mm were cut by using a band saw, followed by a finishing phase to eliminate the edge delamination. All specimens were cut in order to preserve the composite laminate principal directions. The holes were initially carried out by using at first an undersized drilling bits. Afterward, a specific cutting tool (i.e. a mill tool) was used to obtain the bolt diameter minimizing the edge defects with the aid of a sacrificial composite plate located underneath the composite laminates during the drilling. The composite specimens used for bearing tests were designed in order to have different W/D and E/D range ratios. In particular, hole diameter (D) hole center to sample free edge distance (E) and laminate width (W) were varied in the ranges 4–10 mm, 4–18 mm and 13–20 mm, respectively. The geometry of the specimens used for the bearing tests are schemed in Fig. 1. Furthermore, in order to better clarify the design of experiment used for the experimental campaign, Table 1 shows all batches used in bearing tests detailing geometry and sample code. All batches were coded F_X_Y_Z. X, Y and Z are numbers indicating the values in mm of hole diameter (D), hole center to sample free edge distance (E) and laminate width (W), respectively. The hole diameter range was chosen to have a sufficient number of batches in order to represent its effect on the performances and failure mechanisms of the sample under pin-hole test.

The bearing tests were carried out in order to evaluate the structural design and analysis at bearing for flax composite laminates, according to ASTM D5961/D standard (procedure A) [35]. The scheme of joint configuration for the bearing tests is shown in Fig. 2.

The composite specimen was connected to a specifically designed steel plates with the purpose to fix the bolt thus reducing its rotation [36]. A Stainless steel pin was located in the hole and a uniform tensile load P, parallel and symmetric to the center line of the plate, was applied to the plate. The bearing tests were carried out by using a universal testing machine (Zwick Z250), equipped with a 250 kN load cell, at a rate of 0.5 mm/min. For each geometrical configuration (Table 1), three specimens were tested. If all these specimens failed through a specific failure mechanism, it was considered as the predominant one

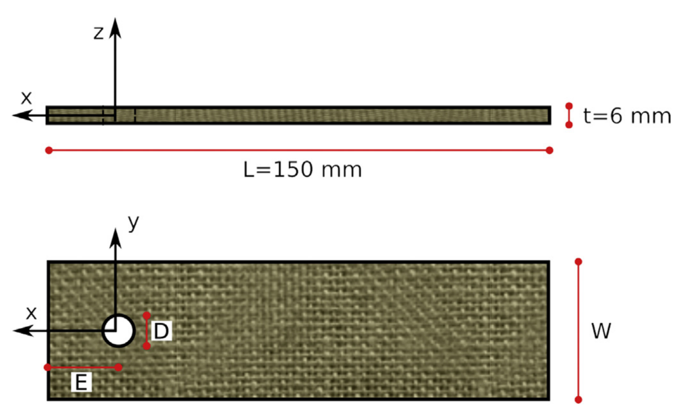

Fig. 1. Geometry of the specimens used for bearing tests.