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Static and dynamic bearing failure of carbon/epoxy composite joints

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ABSTRACT

Mechanical fastening is a common method used to join composite materials in aeronautical industry. Various studies have been performed dedicated to the behaviour of composite bolted joints under quasi-static loadings, but only few studies deal with the dynamic behaviour (crash or impacts). The aim of this work is to study the loading rate influence on the bearing response of a carbon/epoxy laminate loaded by a pin. For that purpose, a double shear test fixture has been specially designed to measure the global behaviour and the local response around the pin. Infrared thermography and Digital Image Correlation techniques have been used to detect, map and characterize dissipative phenomena evolution. The tests have been performed on a servo-hydraulic jack with a loading rate ranging from 10^{-4} m/s to 1 m/s. An increase of the peak bearing load of more than 20% is observed with the loading rate increase. A decrease of the load plateau of more than 60% is obtained. Simultaneous measurements of thermal and kinematic fields in this work give access to the evolution of the damage-related dissipative phenomena close to the pin. These dissipative phenomena were found to be significantly dependent on the loading rate.

1. Introduction

Over the last decades, Carbon Fibre Reinforced Polymers (CFRPs) have been increasingly used in transportation industry, especially in aeronautics, in order to reduce the weight of vehicles. CFRPs represent more than 50% of the mass of the structure of the most recent Airbus and Boeing airliners. Thus, joining composite components to other composite or metallic parts is of utmost importance in the design process of such structures. Mechanical fastening is the most widespread joining method used in aeronautics for composite materials, due to the need of disassembly for maintenance tasks and the lack of reliable non-destructive control methods for bonded joints.

Mechanical fastening of composite laminates has been thoroughly examined in the literature since the 70's. Review articles on the topic can be found in [1] or [2]. First experimental studies of the composite bolted-joint behavior focused on the characterization of the main macroscopic failure modes and influencing parameters on the joint behavior (see for instance [3,4] or [5]). In-plane failure of the joint mostly occurs by tension, shear or bearing failure, or combined failures modes. With laminates, tension and shear are catastrophic failure modes whereas bearing failure is progressive. Bearing failure develops for high width-to–hole-diameter and end-distance-to–hole-diameter ratios. Bearing strength is mostly influenced by the lay-up, the hole-diameter-to-laminate-thickness ratio, the bolt-hole clearance and the fastening technology. In particular, bolt lateral clamping has been shown to significantly increase the laminate quasi-static bearing strength, up to 100%, by preventing out-of-plane damage effects under the washers [6–9]. In complex junctions involving more than a single row of fasteners, the joint failure is also affected by the unequal load distribution between the fasteners [10–15]. The load distribution between fasteners is itself influenced by the stiffness of the single-bolt elementary joint in the loading direction. Consequence of the unequal load distribution in a line of fasteners is that most elementary joints are submitted to a combination of bypass and bearing loadings that triggers a competition between tensile failure mode and bearing failure mode [16]. Fractographic analyses of the bearing failure in laminates show that bearing is due to the accumulation of local damages on the loaded side of the hole. In particular, bearing failure is driven by both fiber-kinking in the load-sustaining plies parallel to the loading direction and delamination between the plies [7,17–21].

The aforementioned studies, deal with quasi-static testing and modeling of the composite joints. However, energy absorption capability of the bolted joint is an important factor for structural crashworthiness. The energy dissipated by one bolted joint is small, but considering the huge number of joints, the sum is no longer negligible at the scale of a complete airliner. Few studies have been published

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about the influence of the loading rate on the global behavior of the joint. Ger et al. [22] compared quasi-static and dynamic response (loading rates of 3 to 5 m/s) of CFRP and hybrid carbon and kevlar fiber reinforced plastics for various joint configurations. The authors concluded that energy absorption as well as ultimate load decreased with increasing loading rates. However, Li et al. [23] pointed out that the inertia effect had not been considered to calculate the dynamic failure load in [22] which could lead to unreliable conclusions. Several CFRP joint configurations with two rivets were tested at loading rates from 0.5 mm/min to 8 m/s in [23]. The authors concluded that increasing loading rate had no significant influence on the joint stiffness and strength, but observed an increase of the total energy absorption of the single-lap joint, mostly explained by a change of failure mode from net-tension to bearing for the highest loading rates. Coherent results were obtained by Heimbs et al. [24] who tested CFRP single-lap countersunk bolted joints up to 10 m/s. Egan et al. [25] investigated single-lap joint behavior of CFRP bolted joints at quasi-static and dynamic (5 m/s and 10 m/s) loading speeds. It was shown that energy absorption of the joint can be maximized by delaying the transition from progressive bearing failure to ultimate failure. Increasing the loading rate tends to favor ultimate failure by fastener pull-through over fastener failure, thus allowing more extensive bearing damage and energy absorption. Pearce et al. [26] studied the response of single fastener single-lap countersunk bolted joints with in-plane loading (bearing) or normal loading (pull-through). Loading rates vary from 0.1 m/s to 10 m/s. Only minor loading rate dependency was observed in pull-through. For the specimen loaded in bearing, a transition was observed from fastener failure at low loading rates to pull-through at 1 m/s and above. The energy absorption capability of bearing mode failure was specifically investigated by Heimbs and Bergmann [27]. A test set-up was devised to continuously pull a bolt through the laminated plate in a configuration somewhat similar to a double-lap pinned joint. Energy absorption was shown to decrease significantly with increasing loading rates in CFRP laminates.

The literature review clearly exhibits that studies related to the loading rate dependencies are classically performed on joints close to the technological solutions. In such cases, the understanding of the rate dependency is complex because of the interaction between the rivet and the composite plate which leads to a competition between bearing of the composite plate and pull-through of the rivet. The present work is focused on the study of the loading rate dependency of the bearing response of composite plates. In Section 2, a specific experimental set-up on a servo-hydraulic jack has been devised on the principle of double shear lap test in order to perform global (load and displacement) and local measurements (digital image correlation and infrared thermography close to the pin) of the bearing response of the composite plate. Experimental results are presented and discussed in Section 3. Tests are performed at different loading rates from 10^{-4} m/s to 1 m/s. Global and local measurement are analysed in order to evaluate the influence of the loading rate on the bearing response.

2. Material and methods

2.1. Preparation of the specimens

The composite plates used in this study have been manufactured from Hexply M21/35%/268/T700GC (Hexcel France) unidirectional carbon fibre prepreg plies based on a third generation epoxy resin system. The laminated plates have been cured under specific cure cycle in a hydraulic press, after hand lay-up. A generic 16-plies quasi-isotropic stacking sequence $[(45/90/\text{-}45/0)_2]_s$ is used in this study (thickness ≃4.02 mm). The specimens have been obtained after two machining operations (cutting and milling with appropriate tools) with the following manufacturing tolerance for the holes: $ø6.35^{+0.02}_{-0.00}$.

The characterisation of the bearing response of the CFRP laminate under quasi-static loading is normalised by the ASTM D5961 procedure [28]. The specimen geometry and dimensions used in the present work are shown in Fig. 1. Because of the holder geometry of the testing machine, two notches have to be machined in the clamped area of the specimen. With this specimen design the value of the geometrical ratios influencing the behaviour of the assembly are: W/D = 5.6 and E/D = 4.7 with D the hole diameter, W the width of the sample and E the distance between the hole and the end of the specimen. Preliminary quasi-static tests have been performed to validate the bearing failure of the selected geometry.

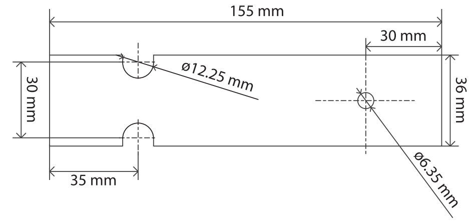

Fig. 1. Specimen dimensions.

2.2. Experimental set-up

The present work is focused on the analysis of the loading rate effect on the bearing failure of the laminate. According to the ASTM D5961 standard [28], the bearing response of the laminate can be studied using either a single-lap configuration or a double-lap test. However, in the case of the single-lap test, the bending effect due to the excentricity of the load path generates out-of-plane effects that can lead to fastener pull-through (see for example [25]). To prevent this unwanted failure mode, a double-lap configuration has been chosen in the following.

A specific double shear test fixture for hydraulic jack has been developed for this study. As it can be seen in the exploded diagram of the Fig. 2, the test fixture brings several improvements with respect to the standard set-up. Metallic plates (numbered 2 and 3) with high elastic limit (Ramax 1400 MPa) are used to transfer the load to a metallic pin. Observation windows have been machined into the plates to enable observation of the specimen surface in front of the pin in the loading direction. The distance between the two plates is controlled by the two spacers (numbered 5 and 6) which ensure sufficient space for the specimen with a clearance of approximatively 0.2 mm (pre-stress is not considered in this study). The spacers also increase the overall stiffness of the set-up and prevent out-of-plane bending of the plates. The two loading plates are linked to the hydraulic jack through the part number 1 in Fig. 2. To avoid relative displacement between the two loading plates during the loading, grooves have been machined into the plates.

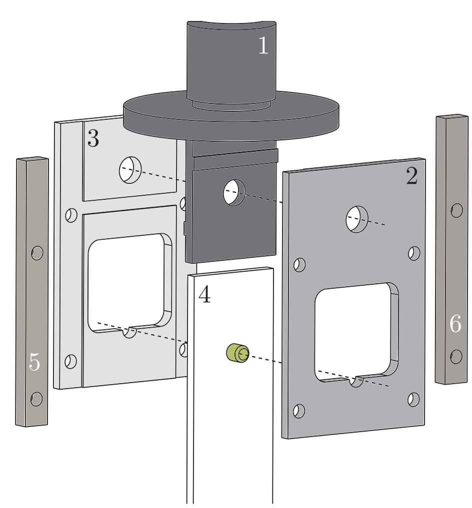

Fig. 2. Exploded diagram of the double shear test fixture.