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Pullout performance of circumferentially notched z-pins in carbon fiber reinforced laminates

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ABSTRACT

This paper presents an experimental study on the pullout performance of circumferentially notched cfrp z-pins in carbon fiber/epoxy laminates. Unidirectional pullout specimens were reinforced with z-pins at a volume content of 1.0%. Four different notch depths were used to investigate their effect on the bridging forces and the dissipated energy during pullout. Compared to smooth z-pins, notched pins were found to provide much higher bridging forces, with the lowest notch depth of 25 μm being the most effective. The debonding force and maximum friction force could be increased up to 87% and 76%, respectively. Because of the enhanced bridging forces, notched z-pins were able to increase the amount of energy that is dissipated during pin pullout. Notching the pins was found to have no influence on the stiffness of the pins during pin pullout. The calculated decrease in strength was 10–28%, depending on the notch depth of the pins.

1. Introduction

The application of fiber-reinforced plastics (FRPs) in the automotive and aerospace industries has been increasing rapidly in recent years. These materials exhibit excellent weight-specific mechanical in-plane properties, and their layered structure of load-bearing fibers and a shaping matrix enables the design of customized lightweight components. However, their high vulnerability to delamination caused by interlaminar stresses, environmental degradation, or impact loads is a long-standing concern of the use of FRP materials. The most common technique for enhancing the delamination resistance of fiber-reinforced laminates made of prepreg materials is z-pinning. Needle-shaped, usually round bars (z-pins) with a diameter of 0.1–1.0 mm are inserted through the thickness of the composite prior to curing to prevent the propagation of delamination cracks. Z-pins are primarily composed of materials with high stiffness and strength, such as steel, titanium, or carbon fiber reinforced plastics. The high potential of z-pins to increase the interlaminar shear strength under mode I [1–4], mode II [1,2,5,6], and mixed-mode loading [7,8], and thereby enhance the impact damage resistance [9–13] of composite laminates, has been demonstrated in numerous experimental and numerical studies.

The mechanism that leads to the enhanced interlaminar fracture toughness of z-pinned composites is generally referred to as the bridging effect. During crack propagation the crack faces are joined together by z-pins. Because of their high stiffness and strength, the pins can absorb a high percentage of the applied load, thus significantly reducing the crack opening stress at the crack front. The bridging forces that are provided by the inserted z-pins during mode I crack propagation can be determined by pullout tests. Investigations on the pullout behavior of composite z-pins in thermosetting FRP revealed that the z-pins are subjected to a sequential three-phase failure mechanism, leading to a complete pullout of the z-pins from the composite laminate [3,11,14–18]. Small crack opening displacements lead to elastic deformation of the pins. In this first phase of the pullout, which is characterized by a linear increase in the bridging force, the z-pins behave as small springs, providing bridging forces that are dependent on their deflection. When the interfacial shear stress exceeds the strength of the pin/laminate interface, the pins are debonded from the laminate. This debonding is accompanied by a sudden decrease in the measured bridging force. In the third phase, the pins are pulled out via a process involving frictional sliding. This phase is characterized by an almost linear slope of the bridging curve until the pins are completely pulled out of the laminate.

A simplified bridging load-displacement curve is shown in Fig. 1. This tri-linear relationship can be described by the characteristic values of the maximum debonding force P_d, the maximum friction force P_f and their associated displacements δ_d and δ_f [16]. The amount of dissipated energy W, determined by the area under the load-displacement curve, is a crucial parameter with regard to the potential of the z-pins to increase the interlaminar fracture toughness of FRP laminates. Since W is strongly affected by the debonding and friction properties of the pin/laminate interface, the aim of numerous studies was to increase the

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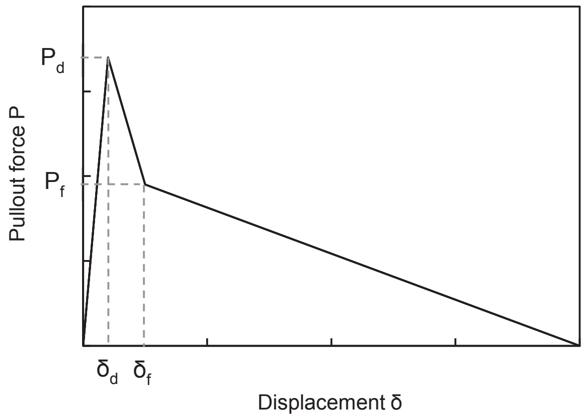

Fig. 1. Simplified tri-linear load–displacement curve and characteristic pullout parameters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

bridging forces by suitable chemical, mechanical, or geometric changes of the pin surface. Considerable effort has been devoted to increase the adhesion between the pin and the laminate, for example, by applicable surface treatments of the pins [19,20], by applying carbon particles or carbon nanotubes (CNTs) on the pin surface [21], or by using different pin resin systems [18]. Wang and Chen [22], as well as Pingkarawat and Mouritz [17], investigated the effect of different pin materials on their pullout behavior. Another effort involved improvement of the pullout performance by changing the cross-section geometry of the z-pins, thereby reducing the stress level within the interface between the pin and laminate [23].

Most of the studies on z-pinning were conducted on composite pins in hot-curing FRP prepreg materials. In this type of laminate, the different thermal expansion coefficients of the z-pins and laminate lead to thermal residual stresses after cooling from the curing temperature. Because of these stresses, the pin/laminate interface is partly or even completely debonded prior to any mechanical loading of the pins [24–27]. This interfacial damage leads to a maximum transmittable interfacial shear stress, which is significantly lower than the expected shear strength when the pin is completely bonded to the laminate. Therefore, a promising approach to increase the maximum debonding force during pin pullout is the creation of form closure between the pin and surrounding laminate. In a prior investigation, Wang et al. [28] were able to increase the bridging forces during pin pullout by using twisted composite z-pins, thus creating a form closure between the pin and laminate. However, they found that a high twisting ratio results in a decrease of the pins stiffness and strength up to 30% and 50%, respectively. In general, a significant loss of strength of the z-pins makes them susceptible to pin rupture during pullout, especially when using high embedded lengths of the z-pins. A sudden failure of the pins leads to a lack of the frictional pullout stage that contributes much of the energy dissipation during crack propagation under mode I loading. Thus, it is highly desirable to enhance the bridging forces by form closure between pin and laminate without a significant deterioration of the z-pin strength.

The aim of this study is to experimentally investigate the effect of circumferential notches on the pullout behavior of z-pins in carbon fiber reinforced laminates under static pullout loading conditions. The influence of different notch depths on the debonding force, the friction force and the dissipated energy is determined for specimens reinforced by CFRP pins that were notched via ultrashort laser pulses.

2. Specimen preparation and test procedure

All test specimens for the experimental investigations on the bridging forces of z-pins were made of carbon fiber-epoxy prepreg (Hexply M21, manufactured by Hexcel Composites). Each specimen contained two laminates separated by a non-stick polytetrafluoroethylene (PTFE) film with a thickness of 25 µm. The unidirectional $[0_{12}/\text{PTFE}/0_{12}]$ test specimens were 40 mm long, 20 mm wide and had a nominal thickness of 4.4 mm. After the lay-up, the laminates were reinforced with z-pins in a 10 mm × 10 mm region at the center of the specimen. To achieve a volume content of 1.0%, the z-pins were arranged in a 3 × 3 pattern with a spacing of 4.25 mm. The pins were made of carbon fiber/bismaleimide rods with a diameter of 0.5 mm (vDijk Pultrusion Products) that were cut into a length of 15 mm. To facilitate penetration of the laminate, one end of the z-pins was sharpened conical. The middle area of the pins was circumferentially notched via ultrashort laser pulses (Fig. 2). To determine the effect of different notch depths on the pullout behavior, z-pins with 25 µm, 38 µm, 64 µm and 72 µm deep notches were manufactured. Specimens with smooth z-pins were tested for reference.

The pins were inserted by using an automatic ultrasonic system with pneumatic heading in the Ultrasonically Assisted Z-Fiber (UAZ®) process [10,29]. The insertion was stopped when the notched area was completely located within the laminate. Subsequently, the compressed foam and the protruding pin tips were removed, and then the z-pinned specimens were cured in an autoclave for 2.5 h at an overpressure of 700 kPa and a temperature of 180 °C. Two T-shaped loading tabs were bonded to the specimens to apply the pullout load. The design of the test specimen and an image of the complete test setup is shown in Fig. 3.

Quasi-static pullout tests were conducted to determine the debonding force of the z-pins and the dissipated energy during the pullout process. Five samples were tested for each notch depth. The z-pinned specimens were loaded in the through-the-thickness direction with a crosshead speed of 1.0 mm/min until all pins were pulled out completely. During testing, the opening displacement was measured using the crosshead displacement of the loading machine (MTS 858). The total load was divided by the number of z-pins within the specimen to determine the average values per pin. Since the recorded displacements also included the deformation of the loading tabs, a separate tensile test

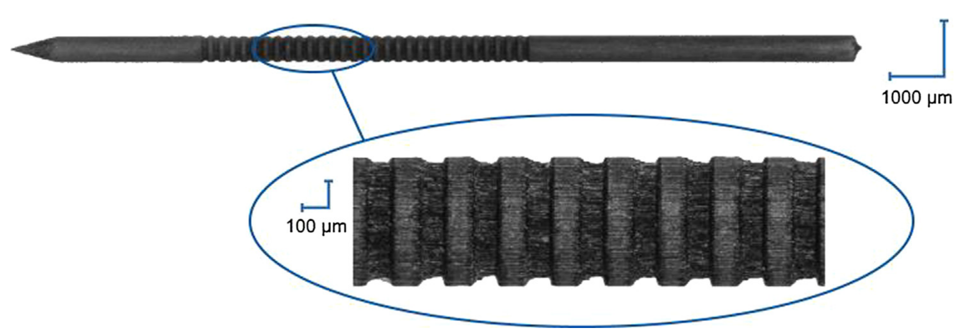

Fig. 2. Notched z-pin and detail view of the notched region in the center part of the pin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)