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Effect of temperature on stresses and delamination failure of z-pinned joints

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Abstract

Although z-pins have been shown effective in preventing delaminations in adhesively bonded and co-cured joints, their applicability depends on a reliable assessment of the strength of a z-pin-composite assembly. In particular, high residual thermal stresses that have been found in experiments dictate the necessity in a local stress analysis. Elevated temperature applied to the joint during its lifetime may also affect its effectiveness in preventing delaminations. The present paper illustrates an approach to determining local residual stresses confirming the observations regarding a possible delamination and cracking in the composite structure due to high post-processing transverse stresses. The analysis of the effect of elevated temperature applied at one of the surfaces on the response of a z-pinned joint is conducted using the concept of a double cantilever beam with an "insulated" crack. In addition, it is illustrated that an elevated temperature may actually benefit the integrity of the joint if it causes an increase in the z-pin-composite interfacial strength.

Keywords: Composite joints; Z-pins; Fracture; Temperature; Residual stresses

1. Introduction

Delamination cracks originating from the edge are recognized as the principal cause of damage and failure in bonded adhesive and co-cured joints. Z-pins, i.e. small-diameter cylindrical rods embedded in the composite material and oriented perpendicular or at an angle to the layer interface, represent a possible method of arresting these cracks. Extensive studies that illustrated beneficial effects of z-pins on various aspects of the behavior of composite structures have been published by Freitas et al. [1], Barrett [2], Lin and Chan [3], Palazotto et al. [4], Vaidya et al. [5] and Mabson and Deobald [6]. In particular, this method may be effective in enhancing fracture and fatigue resistance of co-cured joints between composite skin and stiffeners similar to the joint depicted in Fig. 1.

The advantages associated with using z-pins to reduce or prevent delamination in PMC have been documented in numerous studies. For example, Freitas et al. [1,7] illustrated that a 1.9% volume fraction of carbon z-pins can increase Mode I fracture toughness of laminates by a factor of 18 with only a modest reduction in in-plane tensile strength. Z-pins inclined at 45° have also been shown beneficial for lap shear specimens [8].

Recent studies of z-pinned co-cured joints conducted by the authors on the example of a double cantilever beam (DCB) shown in Fig. 2 have further illustrated the effectiveness of z-pins in preventing fracture and arresting existing delamination cracks [9,10]. Other recently published papers considering z-pin technology dealt with manufacturing aspects of z-pinned laminates [11], experimental evaluation of the z-pin bridging law [12], and thermal residual stresses around z-pin [13]. In particular, the results of a finite element analysis and experimental data presented in the latter paper illustrated the presence of large residual stresses in z-pinned laminates. These stresses could be sufficient to cause failure in a standard matrix resin of PMC resulting in post-processing cracking. Therefore, the first part of the present study justifies and illustrates a simple, yet accurate, computational procedure

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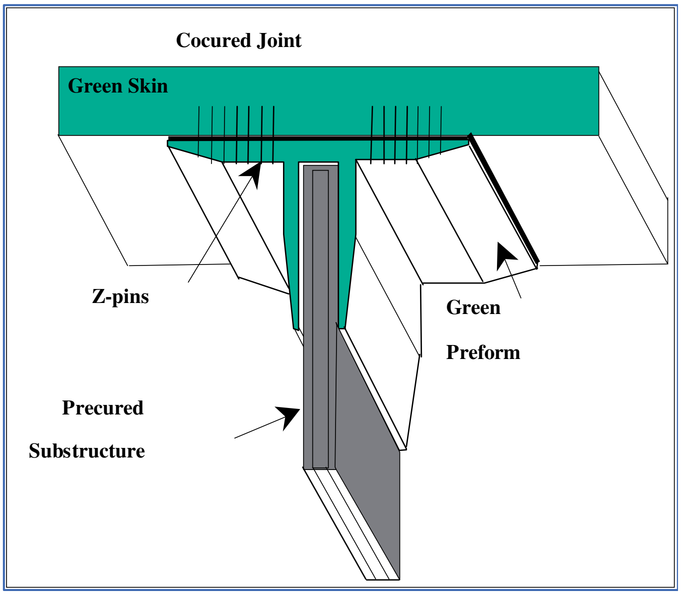

Fig. 1. Co-cured z-pinned joint between the skin and stiffener.

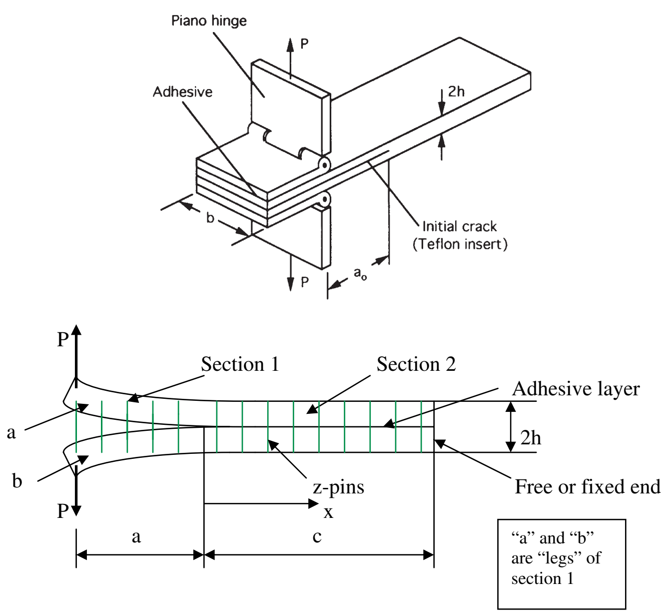

Fig. 2. Schematic illustration of the DCB test, according to ASTM 5528 (from Daniel, I.M. and Ishai, O. Engineering Mechanics of Composite Materials, Oxford University Press, New York, 1994 and ASTM, D 5528-01) and the model used in the analysis of a DCB with z-pins loaded in mode I (Part 3 of the analysis in the paper).

capable of predicting residual thermal stresses in a z-pinned composite laminate.

Thermal loading applied during the lifetime of a z-pinned component produces both local thermal stresses due to the thermal mismatch between z-pins and substrate material as well as a "global" deformation and associated stresses. An approximate approach to estimating the former effect is presented in the second part of the analysis.

The third part of the analysis deals with the effect of elevated temperature on fracture of z-pinned co-cured joints associated with their global thermally and mechanically induced deformations. The paper provides a methodology of the analysis of the effect of z-pins on the integrity of z-pinned co-cured joints for the case of a nonuniform temperature introducing a new concept of "insulated crack" in the DCB test setting. A number of conflicting tendencies may affect the integrity of the joint in the presence of temperature, including variations of the material properties, thermally induced stresses, and changes in the interfacial shear strength between z-pins and the composite material. A large effect of the interfacial shear strength on the integrity of joints undergoing Mode I loading observed in numerical examples leads to the recommendation to employ artificially uneven surfaces of z-pins to maximize their resistance to pullout, even at the room temperature.

2. Analysis

2.1. Part 1: Residual thermal stresses in a z-pinned laminated material

The model (representative cell) employed for the analysis is shown in Fig. 3. Typical z-pin joints contain a large number of z-pins but their volume fraction, i.e. the fraction of the unit volume of the composite material occupied by z-pins, is invariably small, never exceeding 3% (in actual applications, it is usually closer to 1%). Therefore, the model shown in Fig. 3 represents a single pin surrounded by the composite laminated material. The outer radius of the model shown in Fig. 3 is determined from the requirement that the areal density of the z-pin in this model corresponds to the density of z-pins in the actual joint (in case where z-pins are extended through the entire thickness of the composite laminate, the areal density of z-pins is equal to their volume fraction). Accordingly, if the areal

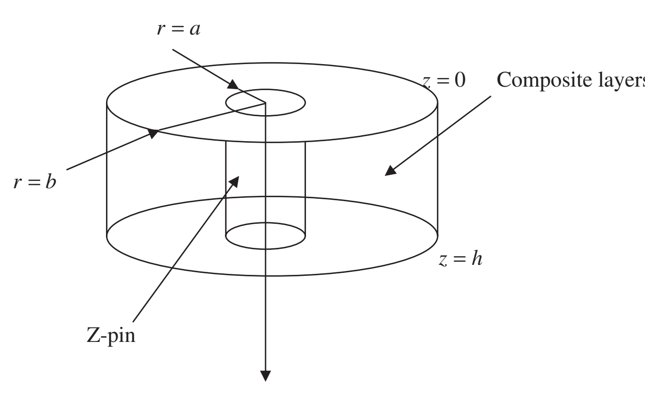

Fig. 3. Model (representative cell) and the coordinate system used in the local analysis. The pin and surrounding composite cylinder are transversely isotropic (both of them are isotropic in the planes $z = \text{constant}$). Composite layers are assumed identical, so that the analysis refers to them as "composite material".