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Numerical simulation of the effect of stitching on the delamination resistance of laminated composites subjected to low-velocity impact

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ABSTRACT

The paper illustrates the use of Finite Element (FE) analyses for the simulation of the effect of through-thickness stitching on the structural and damage response of composite laminates subjected to low-velocity impact. An FE model based on the use of progressive damage schemes for modelling intralaminar and interlaminar damage and accounting for the bridging action of stitching threads was developed in the study. Individual stitches were modelled by solid elements inserted along the thickness of the laminate and connected to the adjacent layer elements through cohesive interface elements. The predictions of the model were assessed by comparison with experimental data obtained by drop-weight impact tests on $[0_3/90_3]_S$ and $[0/90]_{3S}$ carbon/epoxy laminates. The numerical results were found to be in good agreement with the experimental observations in terms of force histories, force-deflection curves and internal damage induced by impact. In particular, the proposed model was able to correctly predict the effect of stitching on the damage response of the laminates at different impact energies and to capture the influence of the layup on the efficiency of stitching for improving the delamination resistance of the laminated samples.

1. Introduction

The role of fibre reinforced composite materials has become increasingly important in many engineering fields, ranging from the aerospace and wind energy industries to the road, railway and marine transport sectors. The high specific static strength and the remarkable fatigue resistance of these materials make them very attractive for structural applications where weight savings, associated with good mechanical properties, are of primary interest. The tailorability to specific loading conditions and the capability of manufacturing complex shape components with a reduced number of assembly steps as compared to metallic materials are additional benefits of this class of materials.

However, while conventional laminated composites usually exhibit excellent in-plane mechanical properties, they are characterized by a high sensitivity to out-of-plane or impact loads [1], as a consequence of the lack of through-thickness reinforcement. The intrinsic weakness of the material along the thickness can easily lead to the initiation and propagation of interlaminar cracks at the interfaces between layers (delaminations); delamination damage is a major concern in the design of primary components, since it may severely impair the load carrying capability and the mechanical performance of the structure, especially under compressive loads.

For this reason, several methods have been proposed to improve the interlaminar fracture resistance of composite laminates. They include matrix toughening [2], enhancement of the fibre-matrix adhesion [3], interleaving [4], use of short-fibre [5] or nanoparticle [6] interlaminar reinforcement, through-thickness stitching and Z-pinning [7]. A comprehensive review of these methods may be found in [8].

Stitching, which consists of sewing a fibre thread (usually glass, carbon, Kevlar® or polyethylene fibres) through a stack of uncured prepreg tapes or of dry fabric layers before curing the prepreg or injecting the resin into the fabric preform [7–9], has proven to be one of the most successful strategies to enhance the interlaminar properties of laminates. Stitching was found to increase the delamination resistance of laminates under static and impact loadings [10,11], and to improve the tolerance to damage and the residual strength of impacted laminates subjected to compressive or tensile loads [12]. The improvements in fracture resistance are generally attributed to the bridging action of through-thickness threads, which apply closure tractions at the interface between delami-

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nated layers, thereby reducing the driving force available for propagation of the interfacial crack [7].

In contrast, the stitching process leads to a distortion of the inner structure of the laminate, introducing localized disturbances and stress concentration regions, such as layer waviness, resin-rich regions and fibre breakage [10], that may act as starting points for additional damage modes in the material.

A significant number of papers have been dedicated to the experimental characterization of the structural and damage response of stitched laminates to low-velocity impact. Most of the studies show that the introduction of through-thickness stitches reduces the delamination area induced by impact, as a result of the improved interlaminar fracture properties of the material. Reductions by up to 50% in the impact damage area were for example measured by Wu and Wang [13] in glass/epoxy laminates stitched by Kevlar rovings and manufactured by resin transfer moulding (RTM). The experimental analyses showed that both the areal density of stitching and the linear density of the thread affected the efficiency of stitches in controlling the delamination resistance of the laminates.

Remarkable reductions in the delaminated area were also observed in quasi-isotropic carbon/epoxy laminates stitched with carbon fibres and subjected to impacts up to 4 J energy [14], and in Kevlar stitched weave fabric composites impacted with energies ranging between 5 and 50 J [15]. Larger improvements in delamination resistance were generally observed with increasing impact energies in both studies.

The effect of the areal density of stitching and of the thread thickness on the impact response of carbon/epoxy laminates stitched with Vectran threads and consolidated by RTM has been extensively investigated by Tan and co-workers [16–19]. The results of their analyses indicate that for low impact energies stitches act as crack initiators (as suggested by the higher matrix crack density observed in laminates with higher stitching density) and are not able to prevent the initiation of delamination. For higher impact energies, however, stitches prove increasingly effective in restraining the growth of delamination, with higher stitching densities corresponding to larger improvements in the delamination resistance.

Similar results were reported in [20–22] for the impact response of cross-ply laminates made with pre-preg carbon/epoxy layers and stitched with Kevlar or polyethylene threads. In particular, it was found that stitching does not inhibit the initiation of delaminations, but induces a clear reduction of the damage area for delaminations sufficiently long to activate the bridging action of stitches. As a consequence, the efficiency of the toughening mechanisms introduced by stitching strongly depends on the extent and nature of the impact damage occurring in the base laminate. As an example [21], stitching was seen to improve the impact damage resistance of $[0_3/90_3]s$ laminates, for which the main delamination was sufficiently large to allow the full development of the stitch bridging zone; in contrast, no increase in delamination resistance was observed in $[0/90]_{3s}$ laminates, which exhibit a damage pattern consisting of small overlapping delaminations unable to activate the toughening mechanism introduced by stitching.

As compared to the amount of experimental investigations, the published research on the prediction of the effect of stitching on the damage response of composite laminates under impact loading is more limited.

Analytical models to predict the role of stitching in improving the resistance to delamination growth in composite beams subjected to mode I or mode II loading have been first proposed by Mai and co-workers [23–25]. The failure mechanisms typical of continuous stitching were identified as debonding of the thread/matrix interface, elastic stretching of the thread, and thread failure; the major contribution to the increase in delamination toughness was attributed to the elastic stretching of stitches, which provide the crack closure (traction) forces at the delaminated interface. To determine the load carried by stitches under mode I loading, the bond between matrix and stitch was supposed to be completely frictional, assuming a constant value for the friction shear stress. For ENF samples, both the frictional shear stress at the stitch/matrix interface and the bending of stitches due to relative sliding of the delaminated arms were neglected and the load carried by stitches was simply evaluated from the elastic elongation of the thread. To simplify the analyses, the load carried by individual threads was finally replaced by an equivalent distributed load in the governing differential equation for beam deflection.

Sankar and Zhu [26] developed an analytical model to predict the effect of stitching on the delamination resistance of impacted composite beams. The model assumes that the delamination propagates under dominant mode II conditions and that the crack-bridging forces are mainly due to the resistance provided by the matrix as the stitches tend to plough through the matrix. The bridging forces are introduced in the equation of motion of the impacted beam as a constant distributed shear traction acting at the delaminated interface. In agreement with most of the experimental data from the literature, the results of the model indicate that the impact energy required for delamination initiation is not affected by the presence of stitches.

The use of Finite Element (FE) analyses is however required to model the response of stitched composites for more complex geometry or laminate configurations, and in the presence of various interacting damage modes such as matrix cracks, multiple delaminations or fibre fracture. Spar elements were adopted in [27] to investigate the potential of stitching for mitigating the interlaminar stresses arising at the edge of a notch in laminated composites subject to uniaxial tensile load. Linear FE analyses were carried out in [28] to study the structural behaviour of stitched composite T-joints subjected to static flexure, tension or shear load conditions; two-node spar elements, with only uniaxial tension or compression capabilities, were used to simulate the action of the stitching threads during debonding and slipping.

The role of stitches in controlling crack propagation at delaminated interfaces was explored in DCB specimens [29,30] and in single lap joints [31] by calculating the strain energy release rate with the virtual crack closure technique. The bridging effect of stitches was again reproduced in the FE models by two-node spar elements, capable of carrying only axial tensile loads. A nonlinear relationship proposed by Jain and Mai [24] was in particular employed in [29,30] to model the mechanical behaviour of the thread during debonding.

Spar elements were used in [16,32] to simulate the toughening effect of stitches on composite laminates in DCB and Compression After Impact (CAI) testing configurations. A nonlinear behaviour, which accounts for different stages of the fracture process (debonding, slack absorption, stitch breakage and pull-out [16]) was assumed for the stitch elements for simulation of DCB tests, while a simple linear response was used for modelling the response of the laminates under CAI tests [32].

Two-node beam elements connecting adjacent layers were used in [14] to simulate the effect of stitches on the damage response of quasi-isotropic laminates to low-velocity impact; similarly, stitching threads were modelled as 3D linear elastic beam elements embedded within the core and the facesheets for investigating the blast resistance of stitched sandwich composites [33]. Solid elements with isotropic properties were adopted in [34] for modelling the through-thickness reinforcement in stitched laminated plates subjected to bending after impact. Perfect bonding was assumed between the stitch and the surrounding laminate.