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Fracture behaviour at tri-material junctions of crack stoppers in sandwich structures

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ABSTRACT

Inspired by a previously published peel stopper design for foam cored composite sandwich structures, three novel markedly lighter peel stoppers were evaluated with respect to their ability to deflect and arrest propagating face debond cracks. Of the three novel peel stopper configurations, C1, C2 and C3, C1 was similar to the previous design, whereas C2 and C3 were modified with layers of glass fibre fabric extending from the peel stopper tip into the face sheet (C2) or into the face sheet/core interface (C3). The previous peel stopper was validated under mode II dominated conditions, but the novel designs were investigated under mode I dominated crack propagation conditions, which are of higher practical relevance. Both quasi-static and fatigue loading scenarios were investigated. The mechanisms controlling crack propagation at the internal peel stopper tip were studied using thermoelastic stress analysis (TSA) and finite element (FE) analysis. The TSA has revealed significant new information about the local stress fields in the vicinity of the tri-material junction (peel stopper tip) as well as the fracture process zone. Configuration C1 was unable to deflect debond cracks consistently, albeit it did so in most cases, whereas it was incapable of achieving crack arrest. C2 and C3 both performed better in that they consistently demonstrated the ability to deflect propagating cracks, whereas only C2 could arrest the cracks consistently as well. Detailed fracture mechanics analyses confirmed and explained the experimental observations.

1. Introduction

A sandwich structure is a layered composite formed by attaching two thin but stiff face sheets to a thick but lightweight core material. Compared to monolithic structures or laminated composites, this structure is well known for its superior bending stiffness and strength to weight ratios [1]. A weakness of sandwich structures is the quality of the bonding between the face sheet and core. Debonds can initiate from manufacturing defects as well as in-service overload or impact. Propagation of the debonded area is often rapid due to the brittle behaviour of the face sheet/core interface bond, leading to face sheet detachment. The result is loss of strength and stiffness, which may lead to catastrophic failure. From a practical point of view it is desirable to suppress the debond propagation so that some of the loading carrying capacity is retained. Therefore attention has been paid to the development of inserts in the core material to suppress interfacial debonding.

In several studies sub-structural elements (i.e. crack stoppers) made from carbon fibre reinforced plastic (CFRP) were proposed and applied to foam cored sandwich components to prevent the propagation of interfacial cracks. Hirose et al. [2,3] introduced semi-circular shaped CFRP rods in the face sheet/core interface to increase the fracture toughness at the edge of the CFRP inserts. In their studies an increase of the critical load was observed as the crack tip approached the CFRP rods, which was attributed to the redistribution of the stresses between the crack tip and the CFRP rods. Rinker et al. [4] integrated a CFRP double-T joint element and a rectangular shaped CFRP element into the core. Sandwich structures with different embedded elements were investigated under fatigue loading and an increase of fatigue life was observed. Although the introduction of different CFRP inserts increases the interfacial fracture toughness, it was not possible to arrest the crack using these approaches. Moreover, the crack stoppers made from CFRP are much stiffer than the foam core material, which result in severe stress concentration that could initiate cracks.

A different concept was proposed by Jacobsen et al. [5–8], where the crack stopper was manufactured from a PolyUrethane

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(PU) material with stiffness properties similar to those of the foam core materials. A key element in the design was to confine and arrest the growth of the interfacial crack. The basic principle of the so-called 'peel stopper' is to deflect the crack away from the face sheet/core interface into the core, so that the crack path follows the boundary of the peel stopper. The functionality of the crack stopper was validated experimentally using three-point bend tests in which sandwich beams with aluminium or GFRP face sheets and Divinycell H60 PVC foam core were studied [5,6]. It was shown that interfacial cracks that were initiated by core shear failure were successfully deflected and arrested by the peel stopper. The purpose of the present paper is to further explore the peel stopper concept. In particular two considerations emerge from the peel stopper design proposed in [5,6]. Firstly, the loading conditions at the debond tip in [5,6] were mixed mode with significant contribution in mode II. However, many realistic loading situations are mode I dominated, hence there is a need to assess the ability of the peel stopper to deflect propagating interfacial cracks under this condition. Secondly, the bulky design of the peel stoppers accompanied by the high density of the PU material suggests that the use of the peel stoppers described in [5,6] will incur a serious weight penalty.

The work described in the present paper investigates the mechanisms controlling crack deflection in the neighbourhood of peel stoppers experiencing mode I dominated loading. The geometry of the peel stopper is modified to reduce its weight. Three new peel stopper configurations are proposed. Thermoelastic stress analysis (TSA) [9] and finite element (FE) analysis are used to derive the crack-tip stress field and to characterise the fracture behaviour in the neighbourhood of the peel stopper to assess the conditions to achieve successful crack deflection.

TSA is based on the thermoelastic effect where a small temperature change on the surface of a material is measured using infra-red (IR) imaging of the structure under cyclic load. For isentropic conditions, the temperature change (ΔT) divided by the absolute temperature (T) is linearly proportional to the change in the sum of principal stresses [9]. Therefore, TSA is used to determine the stress state in the neighbourhood of the peel stopper and to assess the stress evolution during crack growth. As high spatial resolution data can be obtained from TSA, the aim is to investigate the local effects (local stress concentrations) introduced by the different peel stopper configurations and to understand the associated crack propagation mechanisms. A major challenge in obtaining the stress state from an interfacial crack is the large and discontinuous motion induced by the face sheet/core detachment. As the IR detector is stationary and the specimen is moving, each point on the specimen surface is detected by different elements of the detector array. This leads to erroneous measurement of the temperature change as IR detector cannot track the specimen motion. To address the complex motion expected for the mode I dominated loading of the sandwich specimen, a motion compensation technique has been developed [10]. Digital image correlation (DIC) [11] is used to track the specimen motion and incorporate the displacement field for motion correction of each pixel in the IR images.

In addition to TSA, a FE model was developed based on Suo's interfacial crack formulation [12] and implemented as a subroutine in ANSYS. The goal is to study the energy release rate and mode-mixity of a propagating crack at different locations around the peel stopper. Berggreen [13,14] developed the so called Crack Surface Displacement Extrapolation (CSDE) method and implemented it in ANSYS as a subroutine. The method has been successfully used in combination with FE analysis to investigate interface cracks in sandwich structures. The CSDE method is utilised in this work since it enables calculations close to the crack tip while avoiding the oscillations in the solution that derive from the dissimilarity of material properties.

2. Configurations of the peel stopper

Three different configurations of peel stoppers are studied. In all cases the peel stopper geometry is as shown in Fig. 1(a) which is a modification of the original design by Jakobsen et al. [5]. Here the peel stopper is moulded into a 'U' shaped geometry so that the volume of material is significantly reduced, thus reducing the mass correspondingly. The PU material used for the peel stopper is reinforced by a layer of glass fibre fabric as shown in Fig. 1(b). Comparing to the original design, the glass fibre fabric is introduced to enhance the peel stopper fracture toughness and to prevent the crack from penetrating into the peel stopper.

The peel stopper is moulded in a 'U' shape using a mould made of Polypropylene. The polypropylene does not bond with the PU material making it a good choice for the mould tool as extra coatings are not required. The mould is shown in Fig. 2(a) which includes two parts: the lower and upper parts. The fabrication firstly applies the PU material in the lower part of the mould. The PU material is in liquid form and can take the shape of the mould. The UD fibres are then attached to the upper part with the main fibre direction following the arrows as shown in Fig. 2(a). Finally, the upper part of the mould together with the fibres are pressed into the lower part containing the PU adhesive. Fig. 2(b) shows the side view of the assembled mould where the gap between the upper and lower parts are filled with the PU and fibres. The mould is closed tightly using bolts and nuts to contain the material in the desired dimensions. When the mould is fully closed, the excess PU material is driven out by holes drilled in the mould body.

The three different configurations of peel stoppers are shown in Fig. 3. In configuration 1 (C1), the PU material is directly bonded to the foam core. As the 'U' shaped peel stopper has the same wedge angle (10°) as that suggested in the original design, the configuration at the peel stopper tip of C1 remains the same as that of the original peel stopper. In configurations 2 (C2) and 3 (C3) modifications of small material features at the tri-material junction are made. The aim is to change the local effects at the tri-material junction and thereby enabling crack deflection. In C2 the PU material is also directly bonded to the foam, but the glass fibre layer inside the PU material protrudes from the peel stopper tip. The fibre layer is infused together with the face sheet during the manufacturing process. In C3 an extra fibre layer is introduced at the PU/foam interface when the PU material is bonded to the foam. The part of fibre layer behind the peel stopper is attached to the face sheet as for C2.

In the following sections, the ability of the different peel stoppers to deflect the interfacial crack is examined under both static and fatigue loading. The experimental results obtained from the static tests are used to validate FE models of sandwich specimens containing the different peel stopper configurations. The mechanisms controlling the crack propagation in the vicinity of peel stoppers are then studied using both TSA and FE analysis.

3. Test specimens

The sandwich specimens studied in the present work consist of 25 mm cross-linked PVC foam cores (Divinycell H100) and 210 $\mathrm{g\,m^{-2}}$ plain woven E-glass/epoxy composite face sheets. The core materials include two blocks of foam which have been machined to the required geometries using a CNC milling centre; the two blocks of foam are attached to the inner and outer side of the peel stopper as shown in Fig. 3. The fibre layers introduced