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Fatigue crack growth at the face sheet-core interface in a discontinuous ceramic-tile cored sandwich structure

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ABSTRACT

The fatigue failure mechanism of a sandwich structure with discontinuous ceramic tile core is characterized. The sandwich structure in consideration comprises ceramic core tiles bonded to composite face sheet with a compliant adhesive layer. The discontinuous nature of the core results in a non-uniform stress field under in-plane loading of the sandwich. Static tensile tests performed on sandwich coupons revealed first damage as debonding at the gaps between adjacent tiles in the core. Tension–tension fatigue tests caused debonding at the gaps followed by initiation of cracks in the adhesive layer between the face sheet and core. Experimental data for crack length versus number of cycles is collected at various load levels. Crack growth rates (da/dN) are determined based on the experimental data acquired. The energy release rate available for crack propagation is computed using an analytical model and finite element analysis. Mode separation performed using the Virtual Crack Closure Technique (VCCT) revealed that crack propagation is completely dominated by shear (mode II). Fatigue crack growth behavior for the discontinuous sandwich structure is quantified by correlating the cyclic energy release rate with the rate of crack propagation. The loss of specimen stiffness with crack propagation is quantified using an analytical model.

1. Introduction

Sandwich structures with a core consisting of discrete ceramic tiles are typically employed in applications involving dynamic impact loading and penetration resistance. The ceramic tile core is sandwiched between face sheets typically made from a laminated composite. A thin adhesive layer transfers load between the two constituents. Fig. 1 shows a schematic of a discrete tile core sandwich.

Such a sandwich structure differs from a conventional sandwich structure in that there are in-plane geometric discontinuities at the ends of each discrete tile. This discontinuity creates complex load paths through the structure and introduces stress concentrations in the face sheets, adhesive and core, and leads to interlaminar shear and normal stresses in the adhesive interface layer between face and core. Another difference from conventional sandwich construction is that the tiles used for impact and penetration resistance are much stiffer than the face sheets.

Analytical models have been developed to predict the stress state in the sandwich loaded in in-plane tension and shear [1]. This model predicts axial stresses in the face sheets and core, and the interlaminar stresses in the adhesive layer joining them. This model was later extended to incorporate thermal stresses by Gawandi et al. [2] who investigated the distribution of interlaminar stresses in the adhesive layer and the influence of adhesive mechanical properties. The study shows that the interlaminar shear and normal stresses in the adhesive layer display non-uniform distributions and peak near the gap between adjacent tiles. Although the above models provide useful information about stress state in the sandwich under thermo-mechanical loading, they are limited by the assumption of constant through-the-thickness axial stress in the face layers of a sandwich with open gaps. Most actual structures contain an adhesive material in the gaps between the adjacent tiles. Alfredsson et al. [3] developed an analytical model for in-plane tensile loading of a sandwich with adhesive material in the gaps (filled gaps). With this layer, there is a second load transfer mechanism through the tiles that results in the reduction of interlaminar stress concentration at the interface near the gaps. However, in a static and fatigue loading environment such as in-plane tension, the adhesive in the gap debonds first and results in the increased interlaminar stresses at the face-core interface. Consequently, both the filled and open gap solutions are helpful in interpreting the fatigue results generated in this study.

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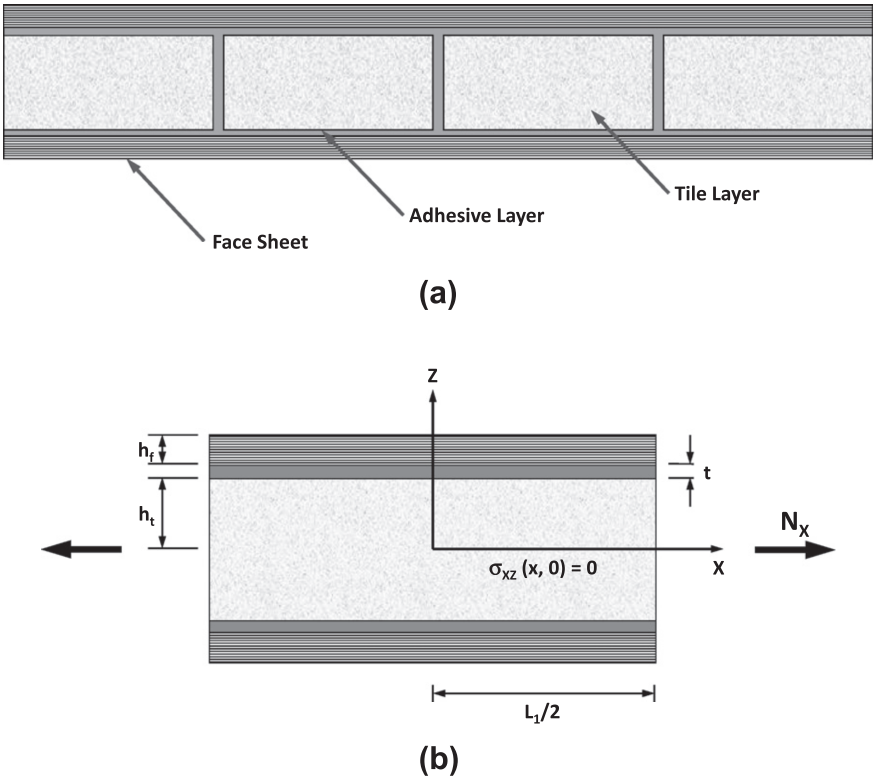

Fig. 1. (a) Discontinuous sandwich structure, (b) unit cell for the sandwich structure.

The presence of interlaminar stresses between face and core in the discontinuous sandwich structure and especially the interlaminar stress concentration near the gap between the adjacent tiles can lead to failure by debonding at the core-face interface. Thus, this location may be the weakest link for the structure with open gaps, see Gawandi et al. [2].

Stress analysis and fatigue of adhesively bonded joints have been considered by many researchers, e.g. [4–9]. Stress analysis of a bonded lap joint shows nonuniform shear and normal stress distributions. Fatigue cracks may initiate and propagate from the site of highest stress in the joint.

Debonding at the face sheet-core interface in statically and fatigue loaded sandwich structures has been investigated by several researchers [10–12]. However, the conventional sandwich construction typically employs a core material much more compliant than the face sheets. The core in the current study is significantly stiffer than the face sheets and can carry a significant amount of applied in-plane tensile load. In conjunction with the discontinuous tile, the interlaminar stress concentrations are significantly enhanced and debonding of the face-sheets under fatigue loading dramatically reduces in-plane stiffness of the sandwich structure.

This paper presents an investigation to characterize the interface crack growth in the discontinuous sandwich structure with a ceramic core. First, materials and geometry used in the sandwich structure are presented. Then, experimental work comprising static and fatigue testing is discussed. Crack length versus number of cycles data is collected from tension–tension fatigue tests. Crack growth rates (da/dN) are determined. Interlaminar stresses and crack growth rate at various crack lengths and number of cycles are studied. Next, the strain energy release rate is calculated analytically and numerically using finite element analysis. Further, fracture mode separation by FEA is achieved using Virtual Crack Closure Technique. Finally, the energy release rate is correlated with the crack growth rate to describe the fatigue crack propagation behavior. The effect of crack propagation on loss of specimen stiffness is quantified using the analytical model.

2. Materials and geometry

The discontinuous sandwich structure comprises the discontinuous core made of alumina tiles sandwiched between the face sheet layers. The length of the alumina tiles determines the length of the unit cell in the structure (Fig. 1b). In the current study, the tile length is 101.6 mm. Each face sheet is a laminated composite structure comprising three-dimensional woven glass fiber in an epoxy matrix. The in-plane fibers in the composite face sheet have a [0/90] layup. The adhesive layer considered in the study is a high elongation elastomeric material. Table 1 provides material properties and dimensions. Sandwich panels were manufactured using Vacuum Assisted Resin Transfer Molding (VARTM) process. The tiles were pre-treated prior to the panel manufacturing to improve adhesion with the interlayer [13]. The test panels are cured at room temperature for 48 h followed by a post-cure for eight hours in an oven at 149 °C. Note that there is no pre-crack created in the test panels at any stage of the experimental investigation. The test coupons for the experimental work are machined from a single panel using a slot grinder with water cooled diamond blades.

Table 1
Material properties and thicknesses for the constituents of a discontinuous core sandwich.

Material	Modulus (E) (GPa)	Poisson's ratio, υ	Thickness (mm)
Tile	345	0.22	10.2
Face sheet	27	0.06	5.08
Adhesive	0.49	0.35	0.508