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DEVELOPMENT OF A METHODOLOGY TO ADDRESS FACE SHEET TO CORE SEPARATION IN SANDWICH STRUCTURES

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1. INTRODUCTION

Typical damage modes in honeycomb sandwich structures include face sheet wrinkling and dimpling, shear crimping, core crushing and core shear failure as well face sheet to core separation (also called disbonding) and core fracture [1]. Face sheet to core separation and core fracture are of particular interest to certification authorities since several in-service occurrences, such as rudder structural failure [2] and other control surface malfunctions [3] have been attributed to face sheet to core separation. Extensive studies have shown that face sheet to core separation can lead to damage propagation caused by internal pressure changes in the core. These internal pressure changes in the core may be due to ground-air-ground (GAG) cycles [4, 5] or may be caused by cryopumping [6, 7]. The increasing use of composite sandwich construction in aircraft applications for instance, composite sandwich construction of the fuselage of business jets that experience higher altitudes than transport aircraft, thus makes it vitally important to understand the phenomenon of disbond growth under generalized load conditions including maneuvers and gust conditions.

In this paper, a detailed problem description is provided first. Second, the overall methodology to address face sheet to core separation in sandwich structures is presented. Third, an overview is given on the development of test methods that yield a critical strain energy release rate associated with disbonding, with a focus on mode-I dominated loading conditions. Forth, an analysis approach is discussed to compute energy release rates along an arbitrarily shaped disbond front. Finally, an outlook is provided.

2. DETAILED PROBLEM DESCRIPTION

A sketch of flat sandwich panel, consisting of laminated composite face sheets and a honeycomb core with an initial disbond at the upper face sheet to core interface is shown in Fig. 1. The honeycomb core is assumed to be unvented. Air flow and rapid pressure equalization with the outside environment is prevented. For this reason, the pressure is initially assumed equal inside and outside the sandwich and thus the sandwich structure is not loaded (and is undeformed), as shown in Fig. 1(a).

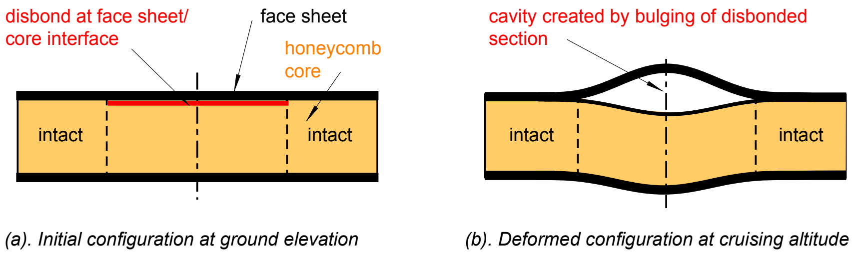


Fig. 1: Deformation behavior of a sandwich panel with disbond.

When the ambient pressure decreases rapidly, for instance during the launch of a spacecraft or the ascent of an aircraft, the resulting pressure difference between the entrapped air and the ambient surrounding air causes the sandwich to expand. In the disbonded section, the thin face sheets with low bending stiffness can easily be deformed by the pressure load and bulge the sandwich as shown in Fig. 1(b). The out-of-plane deformation results in an increased volume, V, creating a cavity and a resulting decrease in internal pressure, p. At the same time, the decreasing ambient temperature cools the entrapped air, causing the honeycomb sandwich to shrink. This combined effect can be calculated using the ideal gas law

$$pV = nRT \tag{1}$$

where T is the temperature of the gas, R = 8.314 J/(mol K) is the universal gas constant and n is the amount of substance of gas (also known as number of moles) [8]. For the face sheet core separation case, the amount of gas is the entrapped air inside the honeycomb cells. Bulging is considered negligible in the intact section. Hence, volume increase is only possible due to out-of-plane deformation of the core. Thus, the pressure change in the intact section is dominated mainly by the temperature change and can easily be calculated using equation (1). For the disbonded section, however, a coupled pressure-deformation problem has to be solved. Therefore, a non-linear finite element analysis has to be performed which couples the ideal gas law for the air-filled cavity with the deformation analysis of the sandwich [9].

3. OVERALL METHODOLOGY

In order to identify, describe and address the phenomenon associated with face sheet to core separation, a reliable method of characterizing this damage mode must be developed. In monolithic laminates, delamination is typically characterized by measuring a critical strain energy release rate, G_c. A similar approach is proposed here, whereby G_c for face sheet to core fracture toughness is measured for a sandwich composite with thin face sheets typically applied in aircraft. However, unlike delamination in unidirectional monolithic laminates, face sheet core separation in a sandwich will not necessarily be confined to the bondline or a particular interface. Studies have shown that disbond growth location can be significantly affected by parameters such as core thickness, face sheet thickness, mode-mix and crack driving force [10, 11]. Characterization tests must therefore be developed that ensure that disbond growth occurs at the location observed in service. Further considerations include identification of a global loading scenario that would be most critical for potential face to core separation, the effect of environmental degradation and thermal residual stresses on disbonding, the potential reduction in disbond growth resistance of a repaired sandwich, and the characterization of disbond growth rates (da/dN vs. ΔG) under cyclic loading conditions. In addition to the characterization tests, analysis tools are required, to help assess the likelihood of a structure exhibiting critical disbonding. These analysis tools need to be verified and validated.

4. DEVELOPMENT OF STANDARD FRACTURE TEST METHODS

Face sheet to core separation generally takes place under mixed-mode loading conditions owing to effects from geometry and the typically disparate properties of the constituent materials of a sandwich structure. Test methods have therefore been developed for measuring fracture toughness associated with mixed-mode loading and also pure mode-II loading [12 ,13]. However, as is the case with delamination in monolithic laminates, the most critical disbonding process in sandwich structure is likely to be mode I dominated, corresponding to loading scenarios where the face sheet is peeled from the core. The literature contains many examples of test methods designed to measure the critical strain energy release rate associated with face sheet/core peel [13-15]. In a recent study, the suitability of five test methods for measuring disbond toughness associated with face sheet/core peel was evaluated [16]. A single cantilever beam (SCB) type configuration, as shown in Fig. 2 was identified as the most appropriate test. This determination was based on the following findings: (1) the test involves a simple loading fixture, (2) disbond front loading conditions were found to be independent of disbond length, (3) disbonding was found to take place along or near to the face sheet/core interface, rather than kinking into the core, (4) the data reduction for computing the fracture toughness can be accomplished using a compliance calibration procedure or the area method [17].

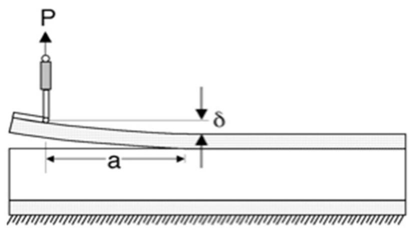


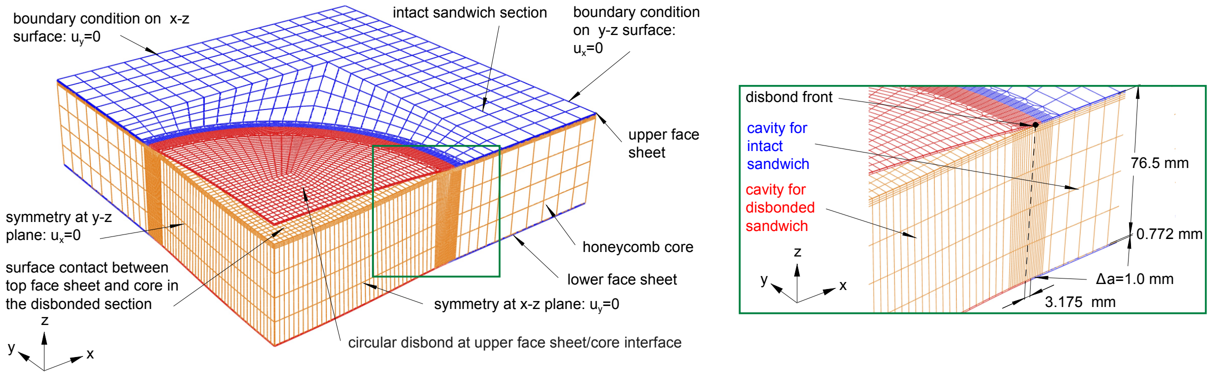
Fig. 2: Single Cantilever Beam Specimen (SCB).

Partly in response to these findings, a recent work item was created in ASTM to develop an ASTM standardized test method for a mode I dominated fracture toughness of sandwich constructions (ASTM WK 47682). As part of the standard development, an *ASTM Draft Standard* was developed, which was used in a round robin activity by seven research laboratories in the US and Europe [18].

5. ANALYSIS METHODOLOGY

Analysis methods are required to help assess the tendency of a structure to exhibit disbond growth. In monolithic laminates, the measured fracture toughness from simple tests is compared to computed values along the delamination front which were calculated from a finite element model (FE) of the real structure. Propagation of the front is predicted to occur when the computed value exceeds the measured fracture toughness of the material. A similar approach is proposed here, where G_c for face sheet to core separation from an existing disbond is measured using the SCB specimen geometry illustrated in Fig. 2. The Virtual Crack Closure Technique (VCCT) is used to calculate the total energy release rate along the disbond front based on the results obtained from a finite element analysis of the disbonded sandwich panel. A typical 3D model of a quarter of a flat panel containing a circular disbond is shown in Fig 3 [19]. Due to the symmetry of the problem, a simple model of a quarter of the panel was used for most analyses to reduce computational time as shown in Fig. 3a. The core was homogenized and 3D volume elements were used for the entire model.

This model was used for an initial study of Ground-Air-Ground-Cycle (GAG) effects in honeycomb sandwich structures. An approach that uses fluid-filled cavities was developed to include the effect of pressure-deformation coupling (recursive process in which deformation results in cavity volume change and thus affects cavity pressure) in the disbonded area of the panel [9]. Therefore, the model was split into two cavities with one representing the intact and the other cavity representing the disbanded section of the panel as shown in Fig. 3b. The influence of the face sheet thickness and core thickness as well as the influence of several honeycomb core materials on the crack tip loading of the disbonded sandwich was investigated. Internal pressure due to GAG-cycle and in-plane loading due aircraft maneuver and gust loads were also applied to the panel [19].



(a). Quarter of a sandwich panel with circular disbond ***(b). Local mesh detail around disbond front***

Fig. 3: Finite element model of disbonded honeycomb sandwich panel.

6. OUTLOOK

Once developed, standardized test methods will be published as *ASTM Standards*. These *ASTM Standards* will be referenced, and methodology, analysis approach, case studies, and guidelines for best practice will be documented in new chapters of CMH-17 Vol. 6 [1].

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