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Facesheet delamination of composite sandwich materials at cryogenic temperatures

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Abstract

A new, novel test method, associated analysis, and experimental procedures are developed to investigate the toughness of the facesheet-to-core interface of a sandwich material at cryogenic temperatures. The test method is designed to simulate the failure mode associated with facesheet debonding due to high levels of gas pressure in the honeycomb core. The effects of specimen orientation are considered, and the results of toughness measurements are presented. Comparisons are made between room and cryogenic test temperatures. It was determined that the test method is insensitive to specimen facesheet orientation and strain energy release rate increases with a decrease in the test temperature. A reasonable agreement between test and simulation was achieved at both temperatures.
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1. Introduction

Future space transportation vehicles will require lightweight structures and materials to meet the increased demands on performance. One area identified as a potential source for significant weight reduction is the replacement of metallic cryogenic fuel tanks with polymeric matrix composite (PMC) tanks. A promising structural concept based on PMC materials is to use a sandwich construction with the PMC as the facesheet material and lightweight polymeric honeycomb materials as the core. As outlined extensively by [1], the sandwich construction technique has many advantages over typical stiffened skin concepts, not the least of which is reduced weight. However, sandwich construction has a number of potential problems because the presence of multiple interfaces serves as a source for failure initiation and growth.

The interest in design of cryogenic-fuel tanks for spacecraft using polymeric composite materials goes back several years to the research associated with the National Aerospace Plane (NASP) and the single-stage-to-orbit (SSTO) vehicles [2]. Concepts were proposed for both the liquid-oxygen tanks and the liquid-hydrogen tanks. These studies addressed weight and cost benefits as well as the complex technical issues such as fatigue crack resistance and oxidation–corrosion resistance. It was recognized that permeation resistance of the tanks could be the overriding design criteria because of the implications that damage and the resulting permeation or leak would have on both durability and safety of the vehicle.

One of the first demonstrations of a PMC cryogenic fuel tank occurred in 1996 when the DC-XA suborbital demonstration vehicle was built with an all-composite liquid-hydrogen fuel tank [3]. The DC-XA tank was designed as an unlined and unstiffened cylinder measuring approximately 2.4 m in diameter. The tank performed as expected in both ground and flight tests.

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It was recognized that the unstiffened shell design would not work for larger tanks and would therefore require some other means to provide global and local stiffening. To avoid the potential weight penalties associated with a stiffened shell design, sandwich construction was considered. For an integrated cryogenic tank (i.e. one that is integral to the airframe structure), the tank wall must carry structural and pressure loads while operating over an extremely wide temperature range. One possible failure mechanism, associated with the use of sandwich materials in such a demanding environment, is debonding of the facesheet. This mechanism can occur due to high gas pressure inside the core material as a result of hydrogen leakage through the facesheet. This mechanism is facilitated by the occurrence of cryopumping. Cryopumping is a known phenomenon and is simply the condensation of a gas on a cryogenically cooled surface to produce a vacuum [4] that can occur during repeated cryogenic fluid fill and drain cycles. For a cryotank with PMC sandwich materials in the tank walls, this cryopumping will occur when the tank wall facesheet(s) develop leaks and allow the cryogen to permeate into the core. Subsequent warming of the cryogen causes a transition from a liquid to a gas phase and results in a substantial increase in core pressure. Without proper venting of this pressure, the core, facesheet, and bondline must sustain the resultant pressure-induced loads to prevent failure of the sandwich material [5]. The most likely initial failure mode due to cryopumping is facesheet-to-core debonding that can lead to crack growth and a total separation of the facesheet.

Most notably, this failure mode occurred in the NASA X-33 reusable flight demonstration vehicle. The X-33 was designed with a large ($8.7 \times 6.1 \times 4.3$ m), conformal tank made from a sandwich construction of polymeric composite skins and phenolic honeycomb core. After successful completion of the first protoflight pressure and loads test, the tank was drained of its liquid hydrogen fuel, and a purge of the tank began. Approximately 15 min after the tank was drained, the outer facesheet and core separated from the inner facesheet along part of the tank wall [6]. It was subsequently determined that many factors contributed to the tank failure however, considering the mechanics of the failure, it was found that the inner tank wall allowed permeation (and hence cryopumping) by way of microcracks in the facesheet. As pressure and strain decreased below that required to sustain the microcrack paths, the leak paths closed. As the tank warmed, the remaining trapped cryogens proceeded to vaporize, creating high pressure in the core. This pressure, coupled with bondline defects, likely caused the debond failure. The failure or debonding location occurred almost exclusively at the core-to-adhesive surface on the inner facesheet side.

The objective of this paper is to provide results on the combined experimental and analytical investigation of the facesheet-to-core debonding failure mode in PMC sandwich materials at cryogenic temperatures. The paper provides details on the material, test fixtures, test specimen design, test methods, model development, and fracture analysis. The experimental studies were performed at room temperature, −196 °C, and −269 °C to provide basic material properties and critical fracture parameters associated with failure. To obtain the fracture parameters, a novel test method was designed to simulate the failure mode associated with facesheet debonding in the presence of pressure in the sandwich core.

2. Material and test specimens

The test specimens were of a sandwich configuration made from an arrangement of composite facesheets, adhesive layers, metallic permeability barrier, and honeycomb core materials. This arrangement is shown schematically in Fig. 1. The test method was based on a three-point bend approach relying on the sandwich beam to react the bending load.

2.1. Materials

The PMC facesheet material used in this study was IM7/977-2 and the laminates consisted of a 15-ply quasi-orthotropic laminate ([45/90/−45/0/−45/90/45/0/45/90/−45/0/−45/90/45]) fabricated with a per-ply thickness of 0.132 mm. Fundamental lamina and laminate properties are given in Table 1 as a function of temperature. The core material was Kevlar 6.0pcf, 3/16” (non-perforated), the adhesive was EA9696AL, and the permeability barrier was 5056-H39 (3.5 mil) aluminum foil. All test panels used in this study were fabricated at the Northrop Grumman Corporation.

For reference purposes, the sandwich *longitudinal* direction was defined as the direction parallel to the core ribbon direction and the *transverse* direction was defined as the direction perpendicular to the ribbon direction (Fig. 2). The core material was manufactured in a regular hexagonal pattern and the average area of the core hexagon was estimated to be 24.2 mm^2. The *inner* facesheet was defined as the laminate to be debonded during tests and the *outer* facesheet was defined as the opposite laminate.

Fig. 1. Schematic of test specimen.