DEVELOPMENT AND EVALUATION OF FRACTURE MECHANICS TEST METHODS FOR SANDWICH COMPOSITES

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ABSTRACT

The goal of this research investigation is to develop test methods for characterizing both the Mode I and Mode II energy release rate associated with facesheet/core delamination growth in sandwich composites. Following the evaluation of several candidate test methods, the selection of a recommended test configuration has been made for both Mode I and Mode II testing. For Mode I testing, the plate-supported Single Cantilever Beam (SCB) test appears to be well suited for a wide range of sandwich materials and configurations. For Mode II testing, an End Notched Shear (ENS) test has been developed. Efforts are currently focused towards establishing recommended specimen dimensions and test procedures towards the development of draft testing standards.

INTRODUCTION

Although the development of test methods for fracture mechanics of monolithic composite laminates has reached a high level of maturity in recent years, relatively little attention has been given to the development of fracture mechanics test methods for sandwich composites. Further, a majority of the efforts to date has focused on determining the fracture toughness of a particular sandwich material or the effects of specific environmental conditions. As a result, there is no consensus on a suitable test configuration or specimen geometry for either Mode I or Mode II fracture toughness testing for sandwich composites.

The objective of this research investigation is to develop test methods for the determination of both the Mode I and Mode II fracture toughness of sandwich composite materials that are suitable for ASTM standardization. To date, the first two phases of a proposed three-year research investigation have been completed and Phase III is underway. Recent accomplishments associated with this research investigation are highlighted in this paper.

MODE I FRACTURE MECHANICS TEST METHOD

A total of five candidate Mode I test configurations were identified for initial investigation[1]. Based on a detailed experimental and numerical investigation of these candidate test configurations, the Single Cantilever Beam (SCB) test configuration was selected. In this configuration, the bottom facesheet is affixed to a lower support plate, to prevent bending deformation in the core and bottom facesheet. As illustrated in Figure 1, an upward load is passed through a single piano hinge bonded to the upper facesheet on the delaminated end of the specimen. Thus, only the upper facesheet is considered a cantilever beam, and thus the name “Single” Cantilever Beam. Variations of the SCB test configuration have been researched by Cantwell and Davies[2] as well as Carlsson et al.[3-7]

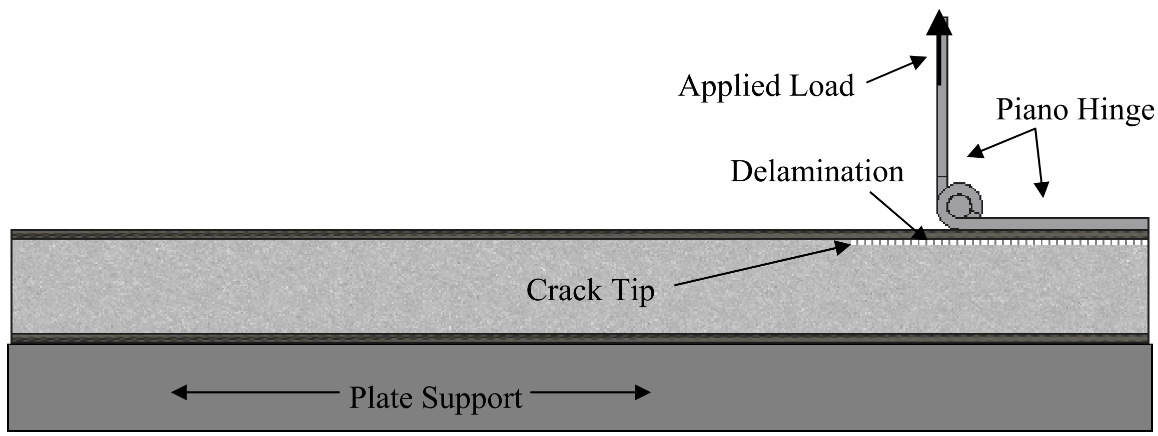


FIGURE 1. SINGLE CANTILEVER BEAM TEST CONFIGURATION

A prototype test fixture was constructed to perform the plate-supported Single Cantilever Beam (SCB) test. This prototype fixture, shown in Figure 2, was designed to accommodate specimen widths ranging from 1 in. to 3 in. The fixture featured a sliding base plate to which the sandwich specimen is secured. A clamping device was developed to secure the lower facesheet of the sandwich specimen to the base plate, thus eliminating the need for adhesive bonding. As loading increases and the delamination along the upper facesheet propagates, the sandwich specimen is allowed to translate (sliding base plate), ensuring that the applied load remains normal to the sandwich specimen.

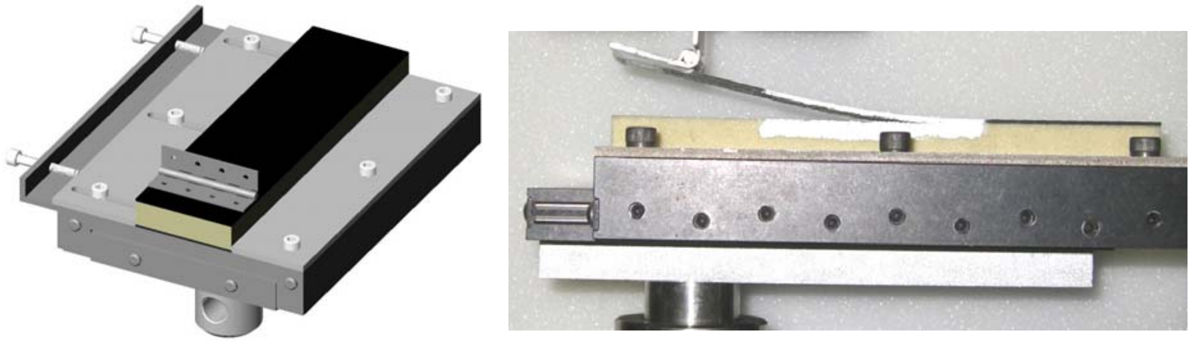
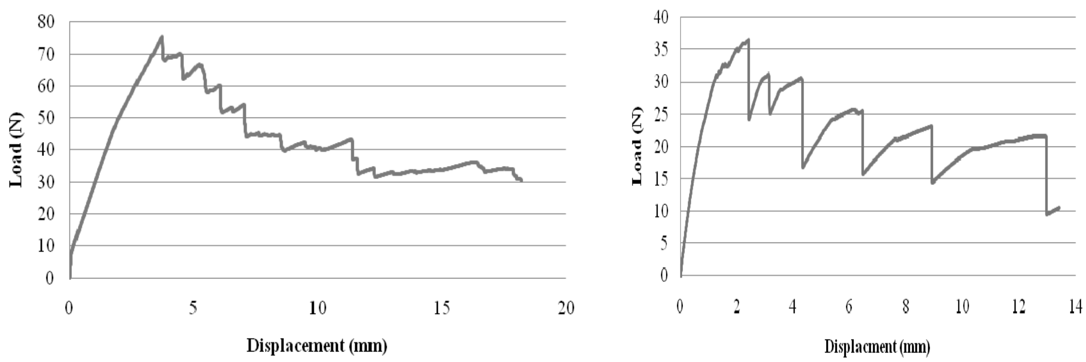


FIGURE 2. PROTOTYPE TEST FIXTURE FOR PLATE SUPPORTED SINGLE CANTILEVER BEAM (SCB) TEST

To date, four sandwich configurations have been used for SCB testing; woven carbon-epoxy facesheets with polyurethane foam and balsa wood cores as well as carbon-epoxy facesheets with Nomex and aluminum honeycomb core. All composite sandwich panels have been fabricated at the University of Utah.

In all SCB testing performed to date, semi-stable, self-similar delamination growth has occurred at the facesheet/core interface without producing secondary failures at other locations in the specimen. Representative load versus displacement plots from SCB testing of Nomex honeycomb core and foam core specimens are shown in Figure 3. The semi-stable crack growth behavior resulted in the crack growing a short distance, then arresting. In general, specimens with honeycomb cores tended to experience more stable crack growth than foam or balsa wood cores.



A. NOMEX HONEYCOMB CORE B. FOAM CORE

FIGURE 3: TYPICAL LOAD VERSUS DISPLACEMENT FROM SCB TESTING

Finite element modeling has focused on the range of sandwich configurations (facesheet and core materials and thicknesses) for which the SCB test method is suited. Of particular interest was the mode mixity (percentage of Mode I) associated with predicted crack growth. Neither facesheet nor core properties were found to have a large effect; a high percentage of Mode I energy release rate was predicted for all materials investigated. Additionally, unless a very low strength facesheet was used with a core material that produced a high critical energy release rate, facesheet failure was not expected.

Recent efforts have focused on identifying the recommended specimen width for Mode I SCB sandwich specimens based on ranges of geometric and material properties of both the core and facesheet. Of interest is minimizing the "edge effects" in the Mode I energy release rate due to anticlastic bending of the facesheet during Mode I loading of the single cantilever beam specimen. Results show a significant width-wise effect, with lower G values at the specimen edge in comparison to the interior of the specimen. Resulting from anticlastic curvature during facesheet bending, these width-wise variations are functions of the Flexural stiffness (EI) of the upper facesheet. As shown in Figure 4, stiffer facesheets (higher EI) produce a lower degree of width-wise variations in Mode I energy release rate. To a lesser degree these variations are also a function of the stiffness of the core. These findings suggest that when designing a sandwich configuration for testing, the facesheet thickness can be increased to reduce such variations. For an already manufactured sandwich configuration, these variations can be reduced by adding a doubler (tabbing) to the top facesheet prior to testing.

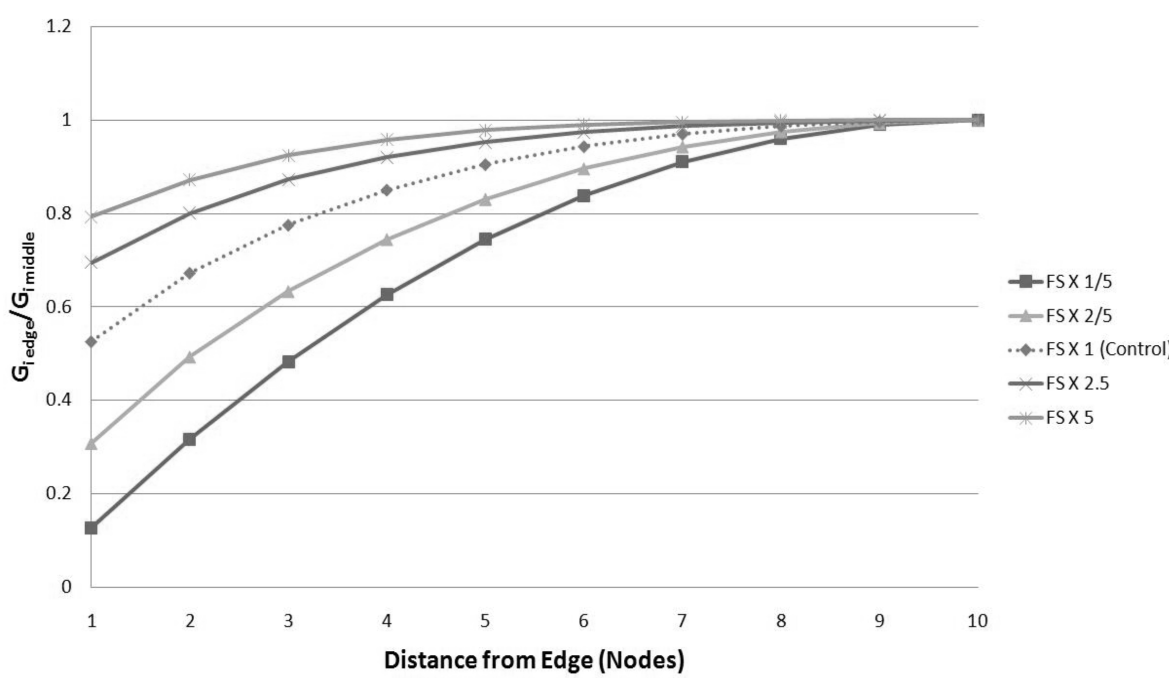


FIGURE 4: FACESHEET STIFFNESS AFFECTS ON WIDTHWISE G_I VARIATION

MODE II FRACTURE MECHANICS TEST METHOD

A total of ten candidate Mode II test configurations were identified for initial evaluation[1]. Following experimental and numerical investigation, the End Notched Shear (ENS) test configuration was selected. This sandwich test configuration was motivated by the three-point end notch flexure test (3ENF) test for monolithic composites. While not an ASTM standard, the 3ENF test is commonly used to determine the Mode II critical energy release rate, G_{IIC} in composites. The test is performed by simply-supporting the specimen near the ends and applying load at the midpoint between the supports. The composite specimen, manufactured with an artificial pre-crack, undergoes flexure, which creates large shear stresses at the crack front and thus Mode II dominated crack growth.

The 3ENF has been modified and adapted to sandwich composites by Carlsson[8] and referred to as the cracked sandwich beam (CSB) test. The transition to a sandwich composite placed the crack at a facesheet/core interface. Further investigation of the CSB configuration by Shipsha et al.[9] showed that unstable crack growth as well as crack growth extending into the core were experienced for foam core sandwich configurations. To address these problems, Shipsha et al. created the Cracked Sandwich Beam with Hinge specimen, where a portion of the core was removed under the crack of the test specimen. A piece of aluminum was adhered to both the top and bottom facesheet with the intention of holding the crack open at the crack front. This method mitigated the frictional forces between the facesheet and core material and facilitated a more stable crack growth condition.

Following testing and analyses of these and other candidate Mode II test configurations[1], the End Notched Shear (ENS) test configuration was developed. As shown in Figure 5, the ENS test is similar to the CSB with Hinge configuration except that the aluminum hinge is replaced by a tensioned wire that fits underneath the top facesheet. This change resulted in an improved stress state and simplified test preparation, as core removal from the specimen was not required and hinge bonding was eliminated.

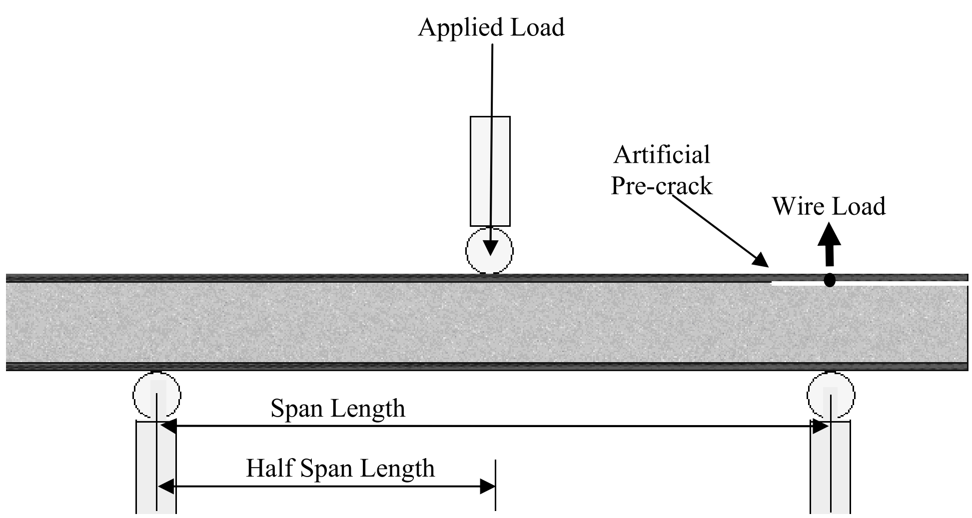


FIGURE 5. END NOTCHED SHEAR TEST

The prototype test ENS test fixture developed is shown in Figure 6. The fixture consists of an existing three-point bend test fixture with an attachment to hold the tensioned wire in place. The attachment consists of a steel frame that supports a 24-gauge (0.5 mm diameter) steel wire. The wire is slid into the crack on the specimen end, and located 2.5 cm from the crack front. After the wire is fixed in place, the specimen is loaded in the same manner as a standard three-point bend specimen. During loading and subsequent crack growth, the wire serves as a mechanism to maintain separation between the facesheet and core, preventing the introduction of frictional forces between the crack faces. The spool and tightening mechanism allow for easy adjustments to the wire tension as well as quick replacement of broken wires. The height of the wire is adjusted at the connection between the steel frame attachment and the three-point bend fixture.

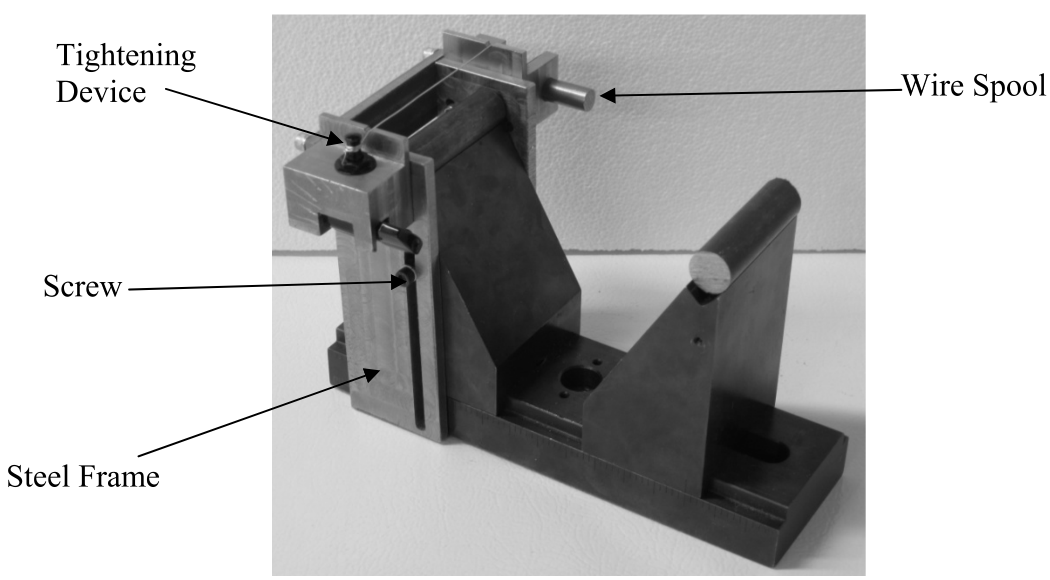


FIGURE 6: PROTOTYPE END NOTCHED SHEAR TEST FIXTURE

End Notched Shear testing was performed on sandwich composite configurations utilizing three types of core and five different facesheets. The three core materials investigated were polyurethane foam, Nomex honeycomb, and aluminum honeycomb. The five facesheets were three, six, and twelve ply carbon/epoxy crossply laminates as well as two and six ply carbon/epoxy woven facesheets. The honeycomb core specimens were adhesively bonded using the three types of cross-ply facesheets whereas the foam specimens were fabricated using the woven carbon/epoxy facesheets and a Vacuum Assisted Resin Transfer Molding (VARTM) process.

Typical force versus displacement results obtained from the ENS testing of Nomex honeycomb core specimens are shown in Figure 7. All nine of the specimens exhibited semi-stable crack growth behavior, allowing for the collection of crack length data for analysis of G_{IIC} values. In all cases, the crack growth occurred along the facesheet/core interface as desired. Similar results were obtained using the other core materials tested. Thus it appears that the ENS test method is suitable for both foam and honeycomb core sandwich composites.

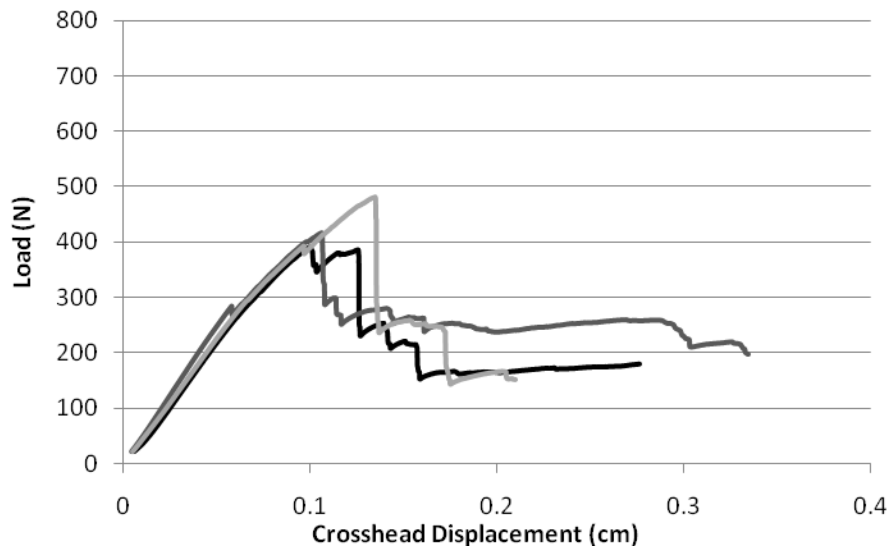


FIGURE 7: REPRESENTATIVE LOAD-DISPLACEMENT CURVES FROM MODE II TESTING OF NOMEX HONEYCOMB CORE SPECIMENS

Further computational modeling has been performed to investigate both specimen width effects as well as facesheet flexural stiffness effects on the calculated energy release rate. Figure 8 shows the predicted variation in both the total energy release rate, $G_{TOTAL,}$ as well as the Mode II component, G_{II} across the specimen width for a Nomex honeycomb core sandwich specimen. The magnitude of G_{II} is shown to decrease near the specimen edges for both specimen widths considered (2.5 cm and 5 cm). However, the significantly larger value for G_{TOTAL} near the specimen edges implies that the crack growth in these regions is Mode I dominant. This effect appears to be reduced for the wider 5 cm specimen. Further investigation into mode mixity, especially with respect to specimen width, is to be performed.

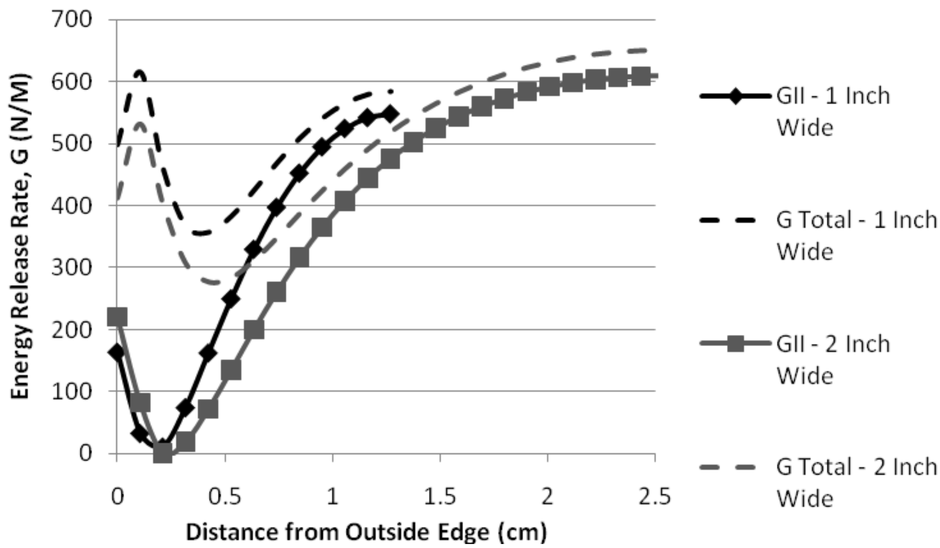


FIGURE 8: ENERGY RELEASE RATE VS. DISTANCE FROM SPECIMEN EDGE

CURRENT AND PLANNED RESEARCH

Current research is focusing on assessing the range of usage for both the proposed Mode I and Mode II sandwich fracture test methods. Of interest are both the geometric parameters (ex: core and facesheet thickness) and material parameters (ex: elastic properties of facesheet and core) of the sandwich specimen. Finite element analysis is being used to investigate ranges of such parameters. Of particular interest is the recommended specimen width to achieve relatively uniform values of energy release rate and the desired mode mixity.

In the final portion of this project, efforts will focus on a final round of testing and analysis to establish the validity of the proposed test methods. Based on results obtained from testing and analysis, a final test configuration and analysis methodology will be selected for both Mode I and Mode II fracture toughness testing. The goal of this final round of testing and analysis is to arrive at a final test fixture design, specimen configuration, data analysis methodology, and a final range of acceptable sandwich materials and geometries for both Mode I and Mode II fracture toughness testing. The final task of this investigation will be the preparation of draft ASTM standards for determining both the Mode I and Mode II fracture toughness of sandwich composite materials.

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