DAMAGE TOLERANCE TEST METHOD DEVELOPMENT FOR SANDWICH COMPOSITES

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ABSTRACT

While damage tolerance testing has reached a high level of maturity for monolithic composite laminates and a standardized test method currently exists (ASTM D7137), little effort has been placed towards arriving at standardized damage tolerance test methods for sandwich composites. The objective of this recently initiated research project is to investigate candidate damage tolerance test methodologies for sandwich composites and to propose specific methodologies for standardization. Three candidate test configurations have been identified to date. The first methodology utilizes an end-loaded compression after impact (CAI) test configuration. Second, a four-point flexure test methodology has been identified for evaluating post-impact performance when the damaged facesheet is loaded in compression. Additionally, a third candidate test method has been developed by the marine composites community. This test method, based upon ASTM D6416, supports the damaged sandwich composite panel on the edges and a distributed load is applied by a bladder until failure. This test methodology is believed to also be of interest for aircraft applications such as fuselages were pressure loadings are present. A secondary focus of this investigation is to provide a comparison of residual strength of sandwich composites obtained using all three of the proposed test methodologies. Initial efforts have focused on performing a preliminary evaluation of the three candidate damage tolerance test methodologies using sandwich composites composed of G11 glass/epoxy facesheets and Nomex honeycomb cores. The three methodologies will be examined for their limits of applicability and recommended procedures. Additionally guidance will be established for interpreting test results and selecting the most appropriate test method for a particular application. Expected benefits to aviation include standardized test methodologies for use in assessing the damage tolerance of sandwich composites used in aircraft structures.

INTRODUCTION

Damage tolerance test method development for monolithic composite laminates has reached a high level of maturity relative to sandwich composites. There currently exists a standardized damage resistance test method (ASTM D7136 [1]), as well as a damage tolerance standard (ASTM D7137 [2]) for monolithic composites. For sandwich composites, relatively little effort has been placed towards arriving at one or more standardized damage tolerance test methods for sandwich composites until recently. However, the need for such a standardized test recently has been identified by the aviation industry in general, and ASTM Committee D30 on Composites specifically. In October 2009, a joint SAMPE/ASTM D30 Panel Session on “Damage Resistance and Damage Tolerance of Sandwich Structures” was held in Wichita, KS. This panel, organized by the PI of this research project, focused on the current status and future needs of damage resistance and damage tolerance test methods for sandwich composites. Considerable interest was identified for standardized damage resistance and damage tolerance test methods for sandwich composites, and work commenced towards a damage resistance test method. In 2011, a damage resistance test method for sandwich composites, ASTM D7766 [3], was published by ASTM Committee D30. Later in 2011, a second joint SAMPE/ASTM D30 Panel on “Damage Resistance of Composite Sandwich Structures” was held in Ft. Worth, TX. At this panel, interest in a subsequent damage tolerance test method for sandwich composites was reaffirmed, and at a later ASTM D30 meeting, the University of Utah (Dr. Dan Adams) was identified as the lead institution to lead the effort towards the development of a standardized test method in damage tolerance.

The objective of this new research project is to develop a test standard for damage tolerance of sandwich composites. The possibility of having multiple methods or practices exists in order to accommodate the largest number of sandwich configurations and loading conditions as well as intended usages of the standard. Additionally, efforts will focus on investigating possible methodologies to scale damage tolerance test results from small-scale sandwich panel tests to larger sandwich structures.

This project has begun with a literature review to identify candidate damage tolerance test methodologies for sandwich composites. Emphasis has focused on both papers and reports in the open literature as well as common practices in the aerospace industry and from commercial test labs. Three candidate test configurations have been identified to date for investigation. The first methodology utilizes an end-loaded compression after impact (CAI) test configuration. Second, a four-point flexure test methodology has been identified for evaluating post-impact performance when the damaged facesheet is loaded in compression. The third test method identified, based on ASTM D6416 [4] applies a uniform pressure to the face of a sandwich panel supported along its edges. An initial evaluation of the three identified damage tolerance test methodologies is underway. For initial evaluation, sandwich composites composed of G10 glass/epoxy facesheets and Nomex honeycomb cores are being used and impact damage will be idealized as a circular hole in the upper facesheet. The goal of these initial tests is to evaluate the three general methodologies for possible standardization. However, a secondary focus will be to provide a comparison of residual strength of sandwich panels with idealized damage using all three of the proposed test methodologies.

LITERATURE REVIEW

The initial task of this research investigation was to review relevant literature as well as published test standards to determine the test methodologies that have been used previously as well as currently in use for assessing damage tolerance of composite sandwich panels. In addition to published literature, common practices in the aerospace industry and from commercial test labs have been investigated. The goal of the literature review was to identify candidate damage tolerance test methodologies for sandwich composites to be investigated for possible inclusion in a standardized test.

A comprehensive report reviewing damage resistance and damage tolerance of sandwich composites has been published by Tomblin et al. [5]. This report summarizes previous investigations focusing primarily on damage modes produced from impact events. Impact energy, facesheet thickness, and core thickness were primary parameters identified for investigating damage resistance. Based on findings from their review, an experimental investigation was performed that focused on impact damage development in sandwich composites and the resulting residual strength of damaged sandwich panels. Additional components of the investigation included investigating damage progression due to cyclic loading, analytical modeling, and correlations with large-scale testing. Recommendations for further study included investigating a wide variety of composite sandwich configurations as well as a wide range of impact energies to investigate different damage modes. The use of a Compression After Impact (CAI) test method was recommended to determine the strength-to-damage size ratio for characterizing the residual strength in terms of impact energy level.

Based on the initial review, three candidate test configurations have been identified to date for investigation. These candidate test methodologies are summarized in the following sections.

Edgewise Compression

One of the most commonly used methods to assess damage tolerance of sandwich composites is edgewise compression testing. Typically, end-loaded Compression After Impact (CAI) testing on sandwich structures has been performed using ASTM D7137 [2], the standardized method for CAI testing of monolithic composite plates, as a reference. This test method requires that the specimen ends are machined to be parallel within tight tolerances, and then loaded edgewise until failure. The specimen sides are supported to prevent buckling failure of the sandwich panel. This test method has been used on Nomex honeycomb panels as well as stitched and unstitched foam panels with success [6-9]. On undamaged or barely damaged high strength specimens it has been found that edgewise loading using this test configuration can lead to undesired failure modes such as end crushing before failure in the gage section [9].

Tomblin et al. [8] and Butterfield and Adams [6,7] have used edgewise compression to assess the damage tolerance of sandwich composites. The sandwich panels tested in both laboratories were 216 mm (8.5 in.) wide by 267 mm (10.5 in.) in height. Impacter diameters of 25 mm and 76 mm (1.0 in. and 3.0 in.) were used.

Whereas the Wichita State University investigation [8] investigated honeycomb core sandwich panels, the subsequent University of Utah investigation [6,7] focused on unstitched and stitched foam sandwich composites. In both investigations, sandwich composites with 9.5 mm and 19 mm (0.375 in. and 0.75 in.) thick cores were tested. Composite sandwich specimens were clamped on the upper and lower loading edges, and knife-edge supports were used on the specimen sides. The test fixture used for the University of Utah investigation is shown in Figure 1. In this investigation, strain gages were placed 25 mm (1.0 in.) from the lower corners in order to align the panels prior to testing. A hemispherical alignment stage, placed under the test fixture, was used in conjunction with the corner strain gages and a small preload to provide proper panel alignment.

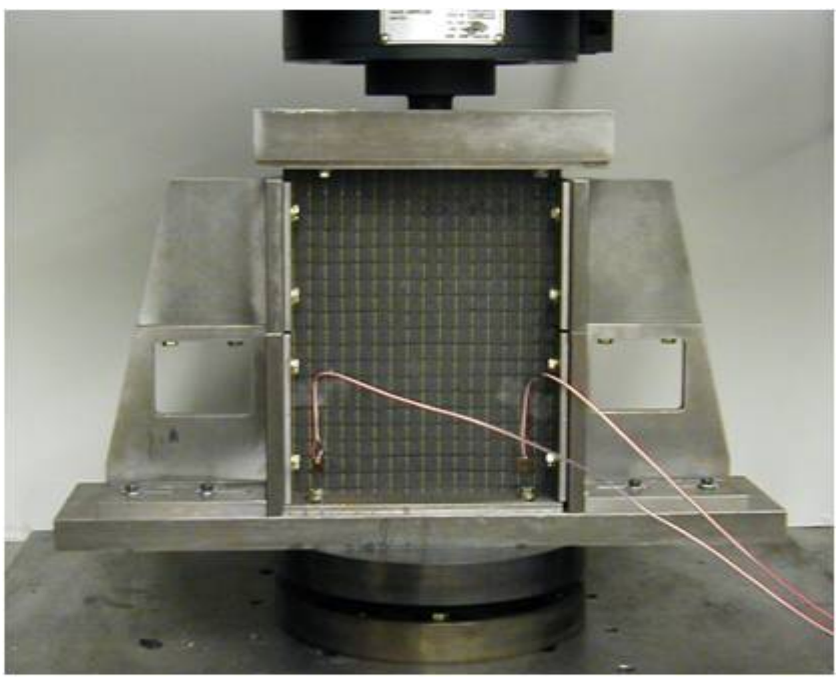

Figure 1. Compression After Impact (CAI) test fixture for composite sandwich panels used at the University of Utah.

Based on the review of the literature as well as from past experiences of the authors, several aspects of sandwich CAI testing have been identified that will require further investigation prior to test standardization. For several core materials, it is necessary to reinforce the core at the specimen ends to allow proper end loading without premature end failures due to either facesheet brooming or buckling. Since an external clamp-type restraint is typically imposed on the sandwich panel at the ends, potting of the entire end of the sandwich specimen is not possible. Rather, the core material must be filled or replaced with a higher strength potting or filler material. Additionally the choice of side supports must be considered. For many sandwich configurations, the sides of the sandwich specimen must be supported to prevent buckling. Such supports may take the form of knife edge supports or clamp-type supports, depending on the type of boundary condition desired; knife edge supports are used to replicate a pinned joint whereas clamped supports are used to minimize panel rotation at the edges. The selection of support conditions are important when considering scaling the results of CAI sandwich panel testing to larger size structures. The best suited size of the sandwich panel as well as the boundary conditions may both be selected to represent the composite structure of interest. Tomblin et al. [5] investigated the effects of scaling the planar dimensions of sandwich specimen both experimentally and using finite element analysis. For sandwich configurations with thin facesheets, the residual strength increased with panel width. However, this increase was not observed for sandwich configurations with thicker facesheets. Results suggest that CAI-level tests may be useful for scaling if the width-to-damage ratio is sufficient to avoid edge effects. This topic will require further investigation for incorporation into the test method under development.

Another aspect of the sandwich CAI test requiring further investigation is the method of specimen alignment. One possible alignment method is to place an undamaged sandwich panel into the fixture and use four alignment strain gages, placed near the bottom corners of the specimen, for alignment. The test configuration is aligned such that approximately equal strains are measured upon application of a preload. Such alignment can be performed using shims, or through the use of an alignment device, such as a hemispherical alignment stage placed under the test fixture as shown previously in Figure 1. Once the specimen alignment is achieved, the fixture is “locked down” such that no further movement is allowed. Subsequent specimens tested with impact damage are tested in the fixture without adjusting the alignment. However, this method does not account for specimen-to-specimen variability in machining tolerances, and requires that the fixture not be displaced between tests. A second method of alignment is similar to the method described above; however adjustments are made for alignment for each specimen tested. While side-to-side alignment generally can be obtained, front-to-back alignment is problematic, due to the impact damage on one surface of the sandwich panel. In general, it is not known whether the strains on the front and back facesheets should be adjusted to be roughly equal under a preload or whether a strain offset due to the nonsymmetrical damage strain is preferred. A third approach, a mixture of the first two, is to use an undamaged specimen to set the front-to-back alignment (which is “locked down”) followed by a test panel specific width-wise adjustment for side-to-side alignment.

Four-Point Flexure

A second candidate test method for damage tolerance testing of sandwich composites is four-point flexure testing. This test configuration allows for a constant bending moment and zero shear stress in the central gage section of the specimen as shown in Figure 2. Using a four-point flexure test allows the damaged facesheet to be placed in either tension or compression loading. In a majority of studies performed to date, the damaged facesheet has been loaded in compression. An example test set-up for four point flexure testing of sandwich composites is shown in Figure 3.

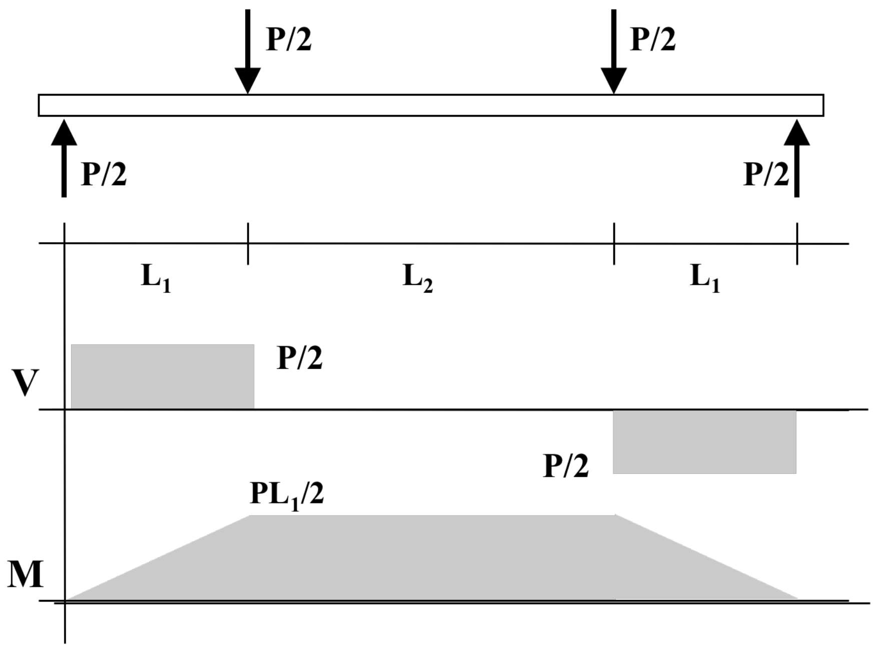

Figure 2. Shear and bending moment diagram for four point flexure test.

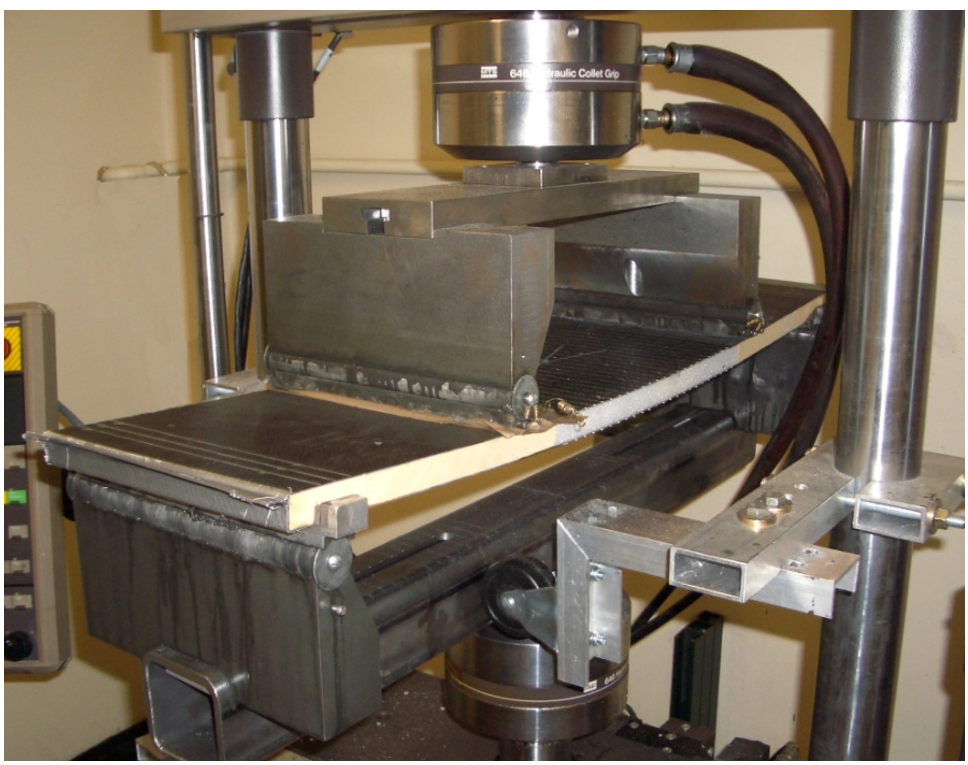

Figure 3. Four point flexure test fixture used for assessing damage tolerance of sandwich composites at the University of Utah.

Based on a review of the literature and past experiences of the authors, a number of aspects of sandwich four-point flexure testing will require further investigation prior to test standardization. The test section, or region of the sandwich panel between the inner supports, must be of sufficient length and width such that the damage present in the panel is not influenced by the panel edges or the presence of the inner loading rollers. Similarly the outer spans of the panel must be of sufficient length to generate an adequate bending moment in the central section prior to shear failure in the outer spans or compression failure at the load application points. Shear failure of the core in the outer spans can be avoided through the use of a higher density core material, or the filling of the cells of a honeycomb core material. Similarly, precautions must be taken to avoid crushing failure of the facesheet and/or core at the loading points. Thus, the sandwich panel and span lengths of the test fixture must be properly designed to prevent undesirable failure modes from occurring under four-point flexure loading.

Distributed Load Plate Flexure

A third candidate test method for damage tolerance testing of sandwich composites is based on the “Hydromat” test configuration, ASTM D6416, [4] that is used to test the residual strength of composite sandwich structures. In this test, the load frame is used to press a water bladder against the test panel as shown in Figure 4. The pressure from the bladder is used to load the sandwich panel. As with the four-point flexure method, the damaged facesheet may be placed in either tension or compression. Currently, this test method is used primarily in the marine industry but may be of interest in any application for which a sandwich structure is pressure loaded.

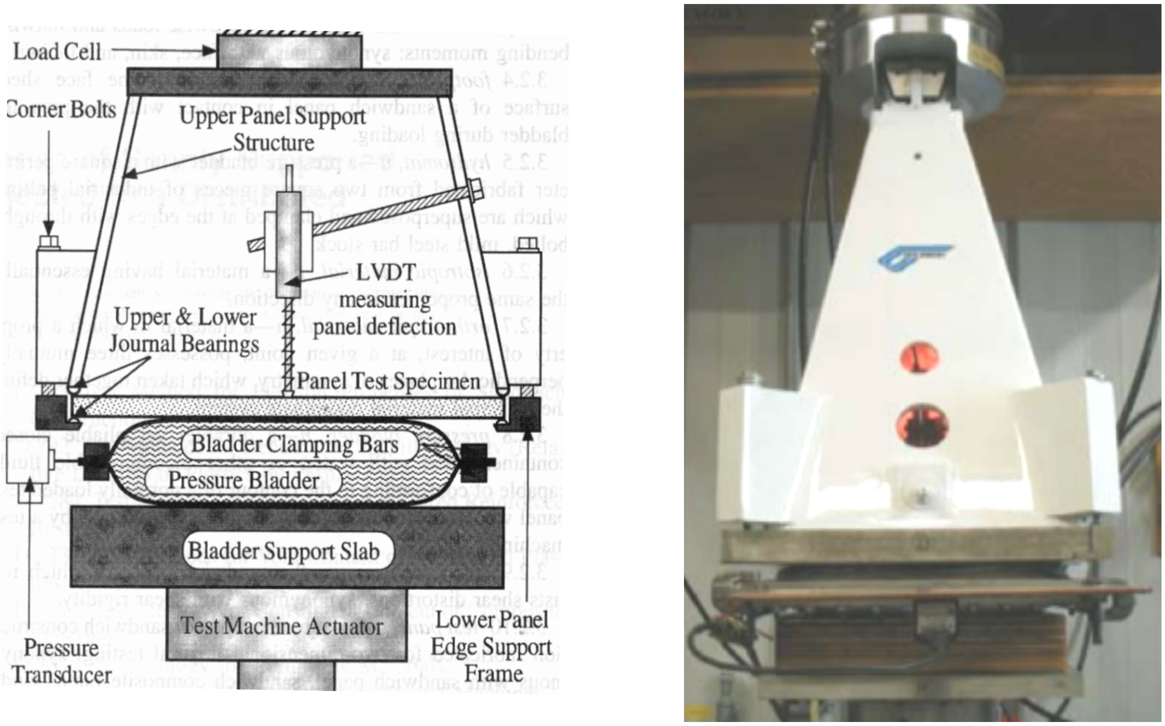

Figure 4. ASTM D6416 "Hydromat" sandwich panel test configuration [10].

INTENDED USAGE OF TEST METHOD

In order to properly develop the proposed test standard, the intended usage(s) of the test must be considered. Possible uses of this standardized test include quality assurance, material selection, product research and development, and the establishment of design allowables. Of these possible uses, the two considered to be the most common uses are for material selection and the establishment of design allowables. Note that if the test method is to be used for material selection, a specific sandwich panel geometry can be specified, along with limitations on facesheet and core thicknesses. If the test method is used for design allowables, however, it must be applicable to as wide of range of composite sandwich configurations (materials and geometries) as possible. Furthermore since the results of such testing would be applied to larger composite structures, a range of sandwich panel sizes and support conditions would be desirable in an effort to scale results up to larger sandwich structures. As a result, it is expected that the ranges of applicability of each proposed test methodology will need to be assessed. Concurrently, efforts to identify the range of sandwich configurations currently used in the aviation as well as other industries will serve to provide practical limits of interest.

INITIAL EXPERIMENTAL INVESTIGATION

An initial round of testing has been initiated to evaluate and compare all three of the proposed test methods for damage tolerance of sandwich composites. Composite sandwich panels have been fabricated from G11 fiberglass/epoxy facesheets bonded to Nomex honeycomb core using FM300 film adhesive. This initial sandwich configuration was selected due to the ease in procuring and producing uniform sandwich panels of sufficient size for the proposed tests. The sandwich specimens for the edgewise compression will be 216 mm (8.5 in.) wide by 267 mm (10.5 in.) in height, the same dimensions as used in previous studies [6-8]. To prevent the loaded ends from crushing prior to failure in the gage section, they will be potted using a room temperature cure epoxy potting compound. The four-point flexure specimens will be 222 mm (8.75 in.) wide by 864 mm (34 in.) long, with a 381 mm (15 in.) inner and 762 mm (30 in.) outer span, similar to previous testing performed at the University of Utah [6,7]. The honeycomb cores in the outer regions of the panels will be filled with an expanding foam filler to prevent core shear failures. Finally, the distributed plate flexure testing will be performed in collaboration with Gougeon Brothers, Inc. using a 305 mm (12 in.) square panel in accordance with ASTM D6416 [4].

To minimize the variability in test results due to variations in damage states, the use of idealized damage in the form of circular holes machined in one facesheet is being employed rather than actual drop-weight impacting. By testing this sandwich configuration with and without the idealized damage, these tests will provide an initial comparison of residual strength among the three candidate test methodologies as well as provide an initial assessment of each method. Additionally, this initial round of testing will be used to initiate a recommended procedure for each test method.

SUMMARY

The focus of this new research project is to identify and evaluate candidate test methods for inclusion in a new test standard for damage tolerance of sandwich composites. Following an initial literature review as well as an investigation into common practices in the aerospace industry and commercial test labs, three candidate test configurations have been identified to date for investigation: end-loaded compression after impact (CAI), four-point flexure, and a “hydromat” pressure loaded configuration. These three methodologies will be investigated to determine their limit of applicability and recommended procedures. A secondary focus of the proposed research will be to provide a comparison of residual strength of sandwich panels following damage for the three candidate test methods. Such a comparison has not been performed to date, and will provide prospective users with guidance on how to select the most appropriate test method and how to interpret test results.

An initial evaluation of the three identified damage tolerance test methodologies is underway. Impact damage is to be idealized as a circular hole in the upper facesheet to minimize the variability in test results due to variations in damage states. These tests will provide an initial comparison of residual strength among the three candidate test methodologies as well as provide an initial assessment of each test methodology.

Expected benefits to aviation from this research project include the development of standardized test methodologies for use in assessing the damage tolerance of sandwich composites used in aircraft structures.

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