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Progressive damage analysis as a design tool for composite bonded joints

Frank A. Leone [a,*], Carlos G. Dávila [a], Donato Girolamo [b]

[a] NASA Langley Research Center, Hampton, VA, 23681, USA
[b] North Carolina State University, Raleigh, NC, 27695, USA

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ABSTRACT

This paper discusses the application of progressive damage analysis (PDA) methods as a design tool. Two case studies are presented in which the effects of changing design features on the strength of bonded composite joints are evaluated. It is shown that the trends of parametric evaluations performed with full-featured PDA models can be unintuitive and the trends can be opposite to those obtained with traditional design criteria. The joint configurations that were tested exhibit multiple damage modes, requiring several different PDA tools to accurately predict the structural peak loads. For damage tolerant structures that exhibit complex sequences of multiple failure mechanisms, traditional failure prediction tools are insufficient. Parametric PDA models encompassing a bonded joint specimen's design space have the potential to reveal unintuitive and advantageous design changes.

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1. Introduction

Fiber-reinforced polymer laminates can exhibit several failure mechanisms, including fiber fracture, matrix cracking, delamination, etc. The first predicted occurrence of one of these failure mechanisms typically does not coincide with structural failure, especially for structures that have been designed according to damage tolerance requirements. Often, structural failure is the result of several different damage mechanisms joining together, progressing from a series of stable and/or locally unstable failure processes up to a globally unstable failure process. For structures whose collapse is preceded by a sequence of different interacting damage mechanisms, the structural strength can be significantly higher than the load that corresponds to the first instance of damage. Failing to take into account the effects of non-critical damage on a structure's ability to carry higher loads can lead to overly conservative structures. In order to accurately predict the strength of a composite structure, it is necessary to predict both the formation of all relevant failure mechanisms and the effects that those failures have on load redistribution.

Progressive damage analysis (PDA) is a broad label applied to several modeling approaches that allow for the prediction of the initiation and evolution of damage. The development and application of PDA tools to advanced composite materials and structures is an active field of research, with several branching technologies that are intended to predict different composite failure mechanisms. Cohesive elements (e.g., [1–3]), for example, excel at discretely representing the formation and evolution of cracks in the finite element (FE) framework when the locations and orientations of cracks are known *a priori* (e.g., delaminations). Continuum damage mechanics (CDM) methods (e.g., [4–8]), rather than discretely representing cracks, represent the presence of various failure mechanisms by changing terms of the local material compliance tensor. CDM-based methods work without having prior knowledge of either the location or orientation of the damage. All PDA methods, however, have multiple strengths and technical limitations in their current state [9]. Having a proper understanding of the capabilities of each method is crucial to selecting the right tool(s) for any given progressive damage modeling application. Often, it is a combination of damage modeling techniques that is required to properly model the initiation and progression of a structural failure process, especially in structures composed of multiple advanced composite materials.

In this paper, the structural response and damage mechanisms of two bonded composite joint concepts from a previous test and analysis campaign are presented [10]. It was observed that several different mechanisms contributed to the eventual failure of the specimens, and that the load at which damage was initially

* Corresponding author.
E-mail address: frank.a.leone@nasa.gov (F.A. Leone).

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observed was well below the structural strength. A combination of PDA tools was used to model the observed sequences of damage events, and good agreement in terms of peak load and failure mode sequence was attained.

Utilizing parametric FE models, it is herein attempted to improve upon the designs of the tested bonded composite joint concepts. Two case studies exploring the integration of PDA methods into the design process are presented. Performing parametric analyses with integrated PDA tools has the potential to yield significantly more efficient designs, to reveal advantageous, unintuitive design improvements, and to reduce the number of physical experiments required to identify optimal configurations.

2. Background

2.1. Test specimens

The development of durable bonded joint technology for assembling composite structures for launch vehicles is an essential component of NASA's Space Launch System. Several joint designs intended for lightly-loaded minimum-gauge space structures were tested in tension, compression, and four-point bending as part of an experimental test campaign at NASA Langley Research Center [11]. Two joint designs from this test campaign are discussed in this paper: a conventional splice joint (CSJ) and a new Durable Redundant Joint (DRJ) concept [12]. Each design involves a honeycomb core with carbon/epoxy facesheets joined with adhesively bonded carbon/epoxy doublers. The data considered in this paper is limited to tensile loading cases.

The sandwich panels used in this study are composed of six-ply carbon/epoxy facesheets and a 25.4-mm-thick Hexcel CRIII-1/8-5052-.0007P-3.1 aluminum honeycomb core. The facesheet material is made of grade 190 TE-1 tapes (toughened epoxy/T800) [13]. The stacking sequence of the facesheets is $[+60/0/-60]_S$, with the 0° fiber direction aligned with the specimen length. The facesheet plies have a nominal thickness of 0.19 mm.

The CSJ specimens measure 559 mm long and 76.2 mm wide and consist of two sandwich panels joined by two 139.7-mm-long, six-ply doublers bonded to the exterior faces of the sandwich with Cytec FM-300M film adhesive, as shown in Fig. 1. At their thickest, the doublers have the same stacking sequence as the facesheets. The doublers have internal ply terminations and ply drops, with cascading ply terminations spaced at 6.4-mm intervals from the doubler edges. Design specifications for the joint specimens allow for a 2.54-mm gap between the sandwich panels. A 12.7-mm-long Teflon film strip was inserted in-line with the adhesive layer at the joint center to decrease the severity of the stress concentration in the doubler at that location.

The DRJ concept expands upon the CSJ design by adding a 96.5-mm-long laminated structural insert in place of honeycomb core at the joint center, as shown in Fig. 2. The insert contains three ±45° hollow, rectangular cells. Six additional plies were laid-up above and below the cells with a stacking sequence of $[+60/0/-60]_S$, with the outermost +60° ply wrapped around all three hollow cells. The DRJ inserts were bonded to the interior surface of the sandwich facesheets using FM-300M adhesive. The inserts are intended to increase the ability of the joint to withstand impact damage and provide nearly symmetric load paths about the facesheet centerlines.

Additional details regarding the CSJ and DRJ concepts, their design, and fabrication can be found in Ref. [11].

2.2. Experimental test results

2.2.1. Conventional splice joint

Two CSJ specimens were loaded in tension to failure. The specimens failed within the joint at peak loads of 109 and 113 kN in similar modes. The first instance of observable damage occurred in the adhesive near the outer edge of the Teflon tape, as shown in Fig. 3a. The asymmetry of the load path in the vicinity of the Teflon tape caused the facesheet to bend away from the Teflon. The bending of the facesheet compressively loaded the core. Because of the light-gauge core used, the two core cells nearest the joint center crushed at approximately two-thirds of the specimen failure load. Without the transverse support of the core beneath the Teflon tape, the facesheet and doubler were free to separate, which induced a mode I loading component of the adhesive and ply interfaces. Since FM-300M adhesive is tougher than the epoxy matrix [10], the delamination transitioned from the adhesive layer to the inner +60°/0° interface of the doubler, as confirmed by inspection of the fracture surfaces in Fig. 3c. Unstable delamination propagation ensued shortly thereafter.

2.2.2. Durable redundant joint

Two DRJ specimens were also loaded in tension to failure. The two DRJ specimens failed at loads of 140 and 130 kN. Failure was observed to initiate as delaminations at two sites in the facesheet: (**1**) below the outermost doubler 0° ply termination, and (**2**) above

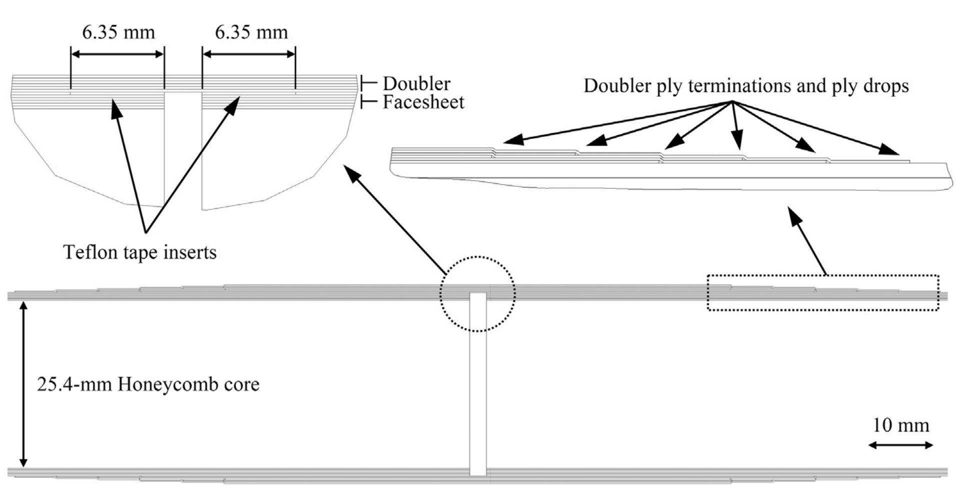

Fig. 1. Schematic of the conventional splice joint (CSJ) cross section [11].

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