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Fatigue life and damage tolerance of postbuckled composite stiffened structures with initial delamination

Carlos G. Dávila [a], Chiara Bisagni [b,*]

[a] NASA Langley Research Center, Structural Mechanics and Concepts Branch, Hampton, VA 23681 USA
[b] Delft University of Technology, Faculty of Aerospace Engineering, 2629HS Delft, Netherlands

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ABSTRACT

The durability and damage tolerance of postbuckled composite structures are issues that are not completely understood and remain difficult to predict due to the nonlinearity of the geometric response and its interaction with local damage modes. A research effort was undertaken to investigate experimentally the quasi-static and fatigue damage progression in single-stringer compression specimens. Three specimens were manufactured with a co-cured hat stringer, and an initial defect was introduced with a Teflon film inserted between one flange of the stringer and the skin. Pre-test finite element analyses were conducted using the virtual crack closure technique to select the range of defect sizes to be considered and the load levels to be applied during the fatigue tests. The tests were monitored with digital image correlation, passive thermography, and ultrasound systems. After an initial opening and extension of the Teflon-induced embedded defect, the specimens sustained a high number of cycles. It was observed that when the skin/stringer separation develops in the opposite flange, it propagates rapidly within a small number of cycles and causes the collapse of the specimen. These test results contribute to a better understanding of the complex response phenomena exhibited by postbuckled stiffened structures subjected to fatigue loads in the postbuckling range.

1. Introduction

Composite stiffened panels used in aerospace structures can sustain loads far in excess of their buckling loads. The collapse of stiffened panels is generally observed deep into the postbuckling range, and it is usually due to the interaction of the postbuckling deformations with local damage modes, in particular skin/stringer separation. The ability to predict the collapse due to static and fatigue loads and the mechanisms involved in the failure is crucial for the assessment of damage tolerance and the rational design of these structures.

Although the high cost of manufacturing prototype composite structures and the difficulty to set up high fidelity tests with a complete set of measurements make these tests quite complex and expensive to execute, there are several sources of well-documented experimental results in the literature that describe the postbuckling response and collapse of composite stiffened structures [1–11]. Most of these studies are concerned with panels under compressive loading, but some regard other loading cases [12–14]. Fewer tests are reported regarding the response of stiffened structures subjected to fatigue loads in the postbuckling range [15–17]. For fatigue loading conditions, the problem is more complex due to the interaction between the geometric nonlinearity of the response, the different possible damage modes, and the accumulation of cyclic damage. These tests are also expensive to conduct due to the length of time that is required.

To address these concerns, single-stringer compression specimens have been evaluated by the authors as a means to study the response and the failure of a multi-stringer panel loaded in compression. In a previous paper by the second author [18], the use of a simple specimen consisting of one L-shaped stringer bonded to the skin was proposed for the study of skin/stringer separation. The specimen was studied experimentally and numerically. Tests were performed investigating the damage propagation using ultrasonic inspection. Finite element analyses were conducted using ABAQUS and the virtual crack closure technique (VCCT).

The present investigation relies on the results of two previous test campaigns performed by the authors on single stringer compression (SSC) specimens composed of co-cured skin and hat stringer [19–21]. The SSC specimen represents an intermediate level of

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* Corresponding author.
E-mail addresses: Carlos.G.Davila@nasa.gov (C.G. Dávila), C.Bisagni@tudelft.nl (C. Bisagni).

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complexity between coupon-level specimens and structural components while exhibiting most of the challenges that characterize the assessment of the damage behavior in a multi-stringer panel. The dimensions of the SSC specimen were determined by analysis and were shown to induce a postbuckling response and failure mechanisms similar to those of a corresponding multi-stringer panel. The SSC specimen is advantageous from an experimental point of view because of its relatively low manufacturing and testing costs. Likewise, from a numerical point of view, the SSC has a lower computational model size requirement.

The first test campaign [19], was used to verify the design of the SSC specimen and to develop a progressive damage finite element analysis. The model was capable of predicting the initiation and propagation of skin/stringer separation as well as the intralaminar damage mechanisms that cause crippling of the stringer, such as matrix cracking, fiber kinking, and fiber fracture, [19]. The finite element model was also used to develop simplified models well-suited to perform sensitivity analyses and to obtain a deeper understanding of the role played by geometric and material modeling parameters such as mesh size and interlaminar strength. In addition, the simplified models were applied within a global/local damage analysis method to predict the damage initiation sites and strength of a multi-stringer panel [20].

The objective of the second test campaign [21] was to characterize more precisely the postbuckling deformation and the sequence of mechanisms that leads to collapse. The specimens were subjected to pre-test ultrasonic (UT) scans to ensure that they were free of manufacturing defects. Their initial deformations were also carefully measured in a coordinate measurement machine. During the test, three-dimensional digital image correlation was used to monitor the formation and evolution of the postbuckling deformations [21]. The study revealed the effects of the interactions of postbuckling deformation modes with the opening of the Teflon film. It was found that minor imperfections due to manufacturing and residual thermal strains can result in vastly different postbuckling responses. Using a high speed camera, it was observed that the collapse was due to skin/stringer delamination followed by crippling of the stringer.

The work presented herein describes the third test campaign performed by the authors and the results obtained. The tests focused on the evolution of damage in SSC specimens subjected to cyclic loads and postbuckling deformations. The specimens were manufactured with a co-cured hat stringer. An initial defect was introduced with a Teflon film inserted between one flange of the stringer and the skin. Three-dimensional digital image correlation was used to monitor the deformation response, and passive infrared thermography was used to capture damage evolution while the specimen was being cyclically loaded. Information obtained from the thermography was used to guide test interruption for more detailed evaluation of the damage evolution using in-situ ultrasonic scans.

2. Single-stringer compression specimen

The configuration of the SSC specimen investigated herein is shown in Fig. 1. The specimen is composed of one hat stringer, with the skin and stringer co-cured [19]. The total length of the specimens is 300 mm, which includes a free length of 240 mm and 30-mm cast tabs at each end. The width of the panel is 150 mm. To investigate the damage tolerance of the SSC specimen, a 40-mm-wide Teflon film was inserted during manufacturing at the specimen mid-length between one flange of the stringer and the skin.

Although the longitudinal edges of the SSC specimen are free and the corresponding locations of the multi-stringer structure are subjected to the restraining effect of the surrounding structure, a comparison of stress distributions between the multi-stringer panel and the SSC specimen shows that, for the particular design under consideration, both panels induce similar stress distributions in the proximity of the stringer [19]. Consequently, the SSC specimen provides a valid configuration for assessing the damage tolerance of the multi-stringer panel and, at the same time, it can reduce the expense associated with testing larger multi-stringer panels.

The entire specimen is made of IM7/8552 graphite-epoxy tape with the properties shown in Table 1 [22]. These material properties are the same ones used in previous investigations [19]. Every ply is nominally 0.125 mm thick. The skin is an 8-ply quasi-isotropic laminate with a stacking sequence of $[45°/90°/-45°/0°]_S$ for a total thickness of 1 mm. The stringer is composed of a 7-ply laminate with a symmetric stacking sequence of $[-45°/0°/45°/0°/45°/0°/-45°]$, which results in a total thickness of 0.875 mm. The loading tabs were cast with a mixture of epoxy resin and aluminum powder. These tabs were machined to precise flatness and parallel conditions to ensure a uniform distribution of the load introduction.

3. Pre-test analysis

Finite element analyses were performed before the tests to determine the size of the Teflon insert to be implanted and the load level to be applied during the fatigue tests. The objective of the analyses was to estimate the load level necessary to induce a noticeable amount of fatigue damage in about 10,000 cycles and collapse before 100,000 cycles. The results of the analyses were used to ascertain that the cyclic load level selected would be unlikely to result in a runout or to cause failure within the first cycle.

A parametric finite element model of the SSC specimen developed for quasi-static collapse [19,20] with the ABAQUS/Standard v6.14 finite element code [23] was adapted for the present study. The model is composed of two layers of S4R shell elements: one for the skin and another for the stringer. Wall offsets were applied so that the nodes for both shell layers were coincident in the flange sections of the stringer. The stringer flanges were connected to the skin with surface-to-surface contact ties with disbond capabilities. The Virtual Crack Closure Technique (VCCT) [24–25] was used as a fracture criterion. A typical element size of 2.2 mm was used, which is considerably coarser than the 0.8-mm density used in previous analyses based on cohesive elements [19]. No initial geometric imperfections were introduced in the model.

Because the propagation of damage from the Teflon-induced defect was the main objective of this test campaign, skin-stringer separation is the only damage mode taken into account by the finite element model. Since intralaminar damage occurs after skin/stringer separation, it was not considered in the present analysis.

The analysis of the SSC specimen consists of a thermal analysis followed by the application of a quasi-static mechanical load. The thermal analysis accounts for the residual thermal stresses that result from contraction of the material during the cool-down after curing. Boundary conditions applied during the thermal step eliminate the free-body motions without inducing reaction loads. After the thermal analysis, out-of-plane restraints are applied to the areas corresponding to the loading tabs and a compression load is introduced through an end shortening displacement. The analyses were conducted using geometric nonlinearity.

The postbuckling deformation of the skin of a SSC specimen obtained by the numerical analysis is shown in Fig. 2(a). As expected, the most pronounced deflections are found along the edges of the skin, and minor deflections are observed on the strin-