Composite Structures 127 (2015) 316–327

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Structural behavior of composite cylindrical splice joint panels under axial compression: Experiments and numerical studies

K. Senthil [a,*], A. Arockiarajan [b], R. Palaninathan [b]

[a] Composites Entity, Vikram Sarabhai Space Centre, India
[b] Department of Applied Mechanics, Indian Institute of Technology Madras, India

ARTICLE INFO

Article history:
Available online 20 March 2015

Keywords:
Debonding
Buckling
Finite element analysis (FEA)
Acoustic emission
Splicer joint

ABSTRACT

Experimental studies and numerical simulations are performed to investigate the structural response of adhesively bonded CFRP cylindrical splice-joint panels subjected to axial compression. Splicer joints used in aerospace composite structures need to sustain the design ultimate loads in the presence of flaws due to manufacturing (debonds), in order to demonstrate compliance with flightworthiness. CFRP cylindrical splice-joint specimens with and without debonds are subjected to compression load. Experimental data reveals that the load-carrying capacity of splicer joint decreases in the presence of debonds. Numerical simulations are carried out in line with experimental observations using finite element analysis. Good correlations with experimental results are obtained both in terms of buckling load capacity and load–displacement responses. Non-destructive methods, pulsed thermography and acoustic emission, are employed to detect and monitor the response of debond respectively. Parametric studies are also performed using finite element analysis to assess the influence of bi-directional loading and the effect of the physical gap provided between basic panels in the splicer joints.

1. Introduction

The use of carbon fiber-reinforced polymer (CFRP) composite cylindrical panels on the launch vehicle structures is extensive. They are primarily used in the upper and interstages as primary load-bearing members. Composite structures are made of segmented cylindrical/conical panels, subsequently splice-joint/doubler-joint is employed in the assembly of the panels. The splice-joint is meant for the hoop continuity in the cylindrical or conical structures, and load transfer is effected by the adhesively bonded joints to ensure uniform stress distribution in the bonded area. However, these joints are susceptible to the presence of defects/flaws, like debonds due to manufacturing. Debonds mean lack of connection between adherents in an adhesive joint, unlike debonding, referred to separation of the fiber–matrix interface in fiber reinforced composites. Though these structures are commonly subjected to different loading conditions, compressive loading has significant role, which may cause buckling. Hence, structural instability becomes a major concern in safe and reliable design of the launch vehicle composite structures. The buckling response of laminated cylindrical panels is necessary to assure the integrity during their service life. Research on the subject of structural response of cylindrical panels under axial compression has been reported by many investigators [1–4]. The buckling resistance of isotropic/laminated cylindrical panels depends on end conditions, geometric variables such as thickness, curvature and aspect ratios [5] and lamination parameters such as ply orientations [6,7]. Bedon and Amadio [8] have investigated the buckling response of GFRP panels subjected to various combinations of in-plane biaxial compressive/tensile loads and reported the effects of various geometrical and mechanical aspects of their load-carrying behavior.

Presence of defects results in significant reduction of in-service mechanical properties and leads to a loss of structural integrity of the composite panels. Among the defects, delaminations and debonds are undoubtedly the most critical for structural resistance. In the literature, various studies have been reported about the buckling behavior of composite plates with through-the-width multiple delaminations subjected to uni-axial compressive load [9–11]. Riccio et al. [12] had studied the influence of the embedded delamination's geometrical parameters on the stability of composite panels under compression. Akbarov et al. [13–15] had an intensive study on the delamination buckling of rectangular elastic and viscoelastic sandwich plate-containing rectangular band, interface inner, and edge cracks under uni-axial and bi-axial-loading conditions. Liu and Zheng [16], Senthil et al. [17] and He [18] gave

* Corresponding author. Tel.: +91 471 2569286; fax: +91 471 2360158.
E-mail addresses: k_senthil1979@yahoo.com, k_senthil@vssc.gov.in (K. Senthil).

http://dx.doi.org/10.1016/j.compstruct.2015.03.044
0263-8223/

comprehensive reviews on the damage modeling and finite element analysis to predict the effect of defects. Studies carried out on the bonded joints by various researchers were reported in the literature [19–21]. Sayman [22] proposed an elastic–plastic multi-linear analytical solution for finding the shear and peel stress in a ductile adhesively bonded double-lap joint. Very few studies have also been reported on the splice-joint laminated panels in the literature. Kim et al. [23] and Senthil et al. [24] investigated respectively on the buckling response of open and closed debonds in adhesively bonded composite splice joints. Nondestructive testing is widely employed in aerospace industries to detect the defects/damages on the composite structures. Genest et al. [25] and Schroeder et al. [26] employed the pulsed thermography technique to detect debonds in adhesively bonded composite joints. Lorriot et al. [27], Liu et al. [28] and Aggelis et al. [29] have used the acoustic emission for detection of damage evolution and study the failure mechanics in carbon fiber/epoxy composite laminates.

Though the studies on the cylindrical laminated panels are reported in literature, it is evident that the studies on the adhesively bonded splice joints are limited. This motivated the study of the cylindrical composite splice-joint panels, which are used in real-life structures. The aim of the present work is to perform a comprehensive investigation on the structural/buckling behavior of cylindrical composite splice joints under axial compression. Specifically, the investigation addresses itself to the following questions: compressive behavior of (1) adhesively bonded cylindrical splice joints, (2) effect of process induced defects (closed debonds), (3) influence of bi-directional loading in the debonded splice-joint and (4) the effects of the physical gap present between the basic panels in the splice-joint. An experimental and numerical study is performed on the intact (nominal) and debonded composite cylindrical splice-joint specimens. A parametric study is conducted to show the influence of bi-directional loading and the effects of the physical gap in the splice-joint. This study provides beneficial information in assisting the design of composite splice joints where its behavior under axial loading is of main concern.

2. Experiments on cylindrical splice joint geometry

This section describes the specimen geometry, fabrication, test setup and test procedure for the axial compression load tests conducted on the intact (nominal) and debonded composite cylindrical splice-joint specimens.

2.1. Materials and specimen preparation

The geometrical details of the cylindrical splice-joint panels considered are: length (a) = 375 mm, inner radius (R) = 1381 mm, thickness (h) = 3.2 mm and the central angle (Φ) is 5° (i.e., the circumferential width (b) of the specimen is 120 mm). The dimensions of the test specimens are arrived based on the detailed study carried out on the typical composite cylindrical splice-joint configurations employed in the launch vehicle structures. The specimen consists of two basic panels, top and bottom side splicers to form the splice-joint (double-butt joint). The stacking sequence of laminated plates is generally designed to be symmetric and balanced to avoid unpredictable warp deflections. In the present study symmetric and balanced quasi-isotropic lay-up sequence is chosen to avoid in-plane property variations.

The basic cylindrical panels have twelve plies, and the splicers have six plies with a stacking sequence of [(0/60/−60/−60/60/0)$_s$] and (0/60/−60/−60/60/0), respectively, and the nominal ply thickness is 0.125 mm. They are manufactured with HTS/M18 unidirectional carbon/epoxy prepreg material. It is cut and hand-placed on a cylindrical steel mandrel having an outer radius of 1381 mm and vacuum bagged. The bagged prepreg laminate is autoclave cured with the following cure cycle recommended by the manufacturer. The material is heated from room temperature (RT) to 175 °C at 3 °C/min and held for 2 h. The autoclave is pressurized to 4 bar and the laminate remains under 0.8 bar vacuum throughout the process. Initially the basic panels and splicers are fabricated with 400 mm length and 160 mm circumferential width, and then trimmed to the test specimen dimensions using a diamond saw. The in-plane elastic properties of unidirectional laminae are shown in Table 1. The in-house developed two compound epoxy-adhesive "EPG 2601 part A and part B" with a mixing ratio of 100:15 is used to bond the basic panels and splicers. The nominal adhesive thickness at each interface between basic panels and splicers is 0.1 mm. The mechanical properties of the adhesive are as follows: Young's modulus 2600 MPa, tensile strength 63 MPa, ductility 3.9%, and Poisson ratio 0.3. One aluminum tab of the same curvature as that of the laminates with 2 mm thickness and 16 mm width are bonded to both sides of each loaded edges using EPG 2601 epoxy adhesive to ensure the uniform load transfer. Also the aluminum tabs are fastened using M4 steel fasteners at the loaded edges of the specimen. Fig. 1 shows the schematic configuration of the intact (nominal) cylindrical splice-joint specimen.

To study the effect of the process induced defects, an artificial debond of size 180 × 45 mm which is equal to 18% of the bond area, is introduced in the cylindrical splice joint specimen by placing polyester film of 50 μm on both basic panel and splicer at the intended location, and in the rest of the areas, adhesive is applied. Debond is located at one-fourth of specimen thickness from the top surface. The details of the debonded cylindrical splice-joint specimen is shown in Fig. 2. Five numbers each of both intact (without debond or nominal, namely N1–N5) and debonded (namely D1–D5) cylindrical splice-joint specimens are fabricated for the experimental study. All the test specimens are subjected to non-destructive inspection (NDI) technique, pulsed thermography to assess and obtain an image of debond area in the intact and debonded test specimens respectively. The flash-pulsed thermographic system called EchoTherm from Thermal Wave Imaging, Inc. is used with MOSAIQ software to process the images. The specimen is heated with a short flash from a Xenon flash lamp on its top surface. The top surface of the specimen is heated up during the flash afterward the heat diffuses into the material. In case of debonds or voids, heat diffusion is altered, and the temperature becomes higher in the top surface of the debond region than the surrounding material. The thermographic images of intact and debonded specimens before testing are shown in Fig. 3.

2.2. Experimental setup and test procedure

The buckling experiments are conducted on ten specimens of which five specimens are intact (nominal) specimens (without debond, named N1 to N5), and the rest five specimens have artificial debond (named D1 to D5) at the bonded interface as shown in Fig. 2. The test setup is designed to simulate the clamped–clamped boundary conditions on the shorter edges of the specimen. In fact, aluminum rectangular blocks with groove having the curvature as

Table 1
Laminae properties for HTS/M18 unidirectional prepreg.

Elastic properties			
Fibre direction modulus	E_{11}	137,000	MPa
Transverse modulus	E_{22}	9000	MPa
In-plane shear modulus	G_{12}	4600	MPa
Poisson's ratio	υ_{12}	0.293	