International Journal of Adhesion and Adhesives 82 (2018) 41–49

Contents lists available at ScienceDirect

International Journal of Adhesion and Adhesives

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

Experimental and numerical studies of stepped-scarf circular repairs in composite sandwich panels

Emna Ghazali, Marie-Laure Dano*, Augustin Gakwaya, Charles-Olivier Amyot

Department of Mechanical Engineering, Université Laval, 1065 avenue de la médecine, Québec, Canada

ARTICLE INFO

Keywords:
Composite sandwich structures
Adhesively bonded repair
Finite element analysis
Progressive damage

ABSTRACT

This paper investigates the static mechanical performance of bonded circular repairs on sandwich panels made with carbon-epoxy composite skins and a Nomex core. First, the mechanical behaviour of pristine, open-hole and repaired sandwich panels under edgewise compressive loading is studied. Next, pristine and repaired sandwich beams are tested under four-point bending with the circular repair loaded in tension. Then, finite element analyses are performed to predict the strength of the repaired sandwich panel. The adhesive film was considered as an elastic-plastic material with a shear failure criterion. The honeycomb core is assumed to behave as a linear elastic material while for the composite skins, a progressive damage model for woven fabric composites is used to predict the skin behavior until rupture. The good agreement between stiffness and strength levels obtained for both experimental measurements and finite element predictions, for pristine, open-hole and repaired sandwich panels, indicates that an effective analysis tool for the mechanical behavior of the repaired panels has been set-up.

1. Introduction

Since fiber-reinforced composite structures offer superior strength, higher stiffness, lighter weight and greater durability [1], they are increasingly being used for primary aircraft components traditionally made of metallic materials. However, despite their good properties, composite airframe structures are more sensitive to impact damage which can cause disbonding, delamination and internal crushing. Considering their extended service life and operating conditions, the extent of damage determines whether the composite components need to be repaired or replaced. Hence, to take full advantage of their many benefits, it is necessary to ensure that these structures are durable, repairable, and maintainable. Since fiber-reinforced composite sandwich structures are increasingly being used in aircraft components, it has become necessary to develop effective repair methods that will restore the component's original design strength.

Several studies have been conducted on bonded scarf and stepped joint repairs of monolithic composites laminates. Campilho et al. [2–7] have conducted a lot of work to study the effects of different repair parameters (scarf angle, lay-up, adherend thickness) on the performance of repaired laminated structures. They used three-dimensional (3D) finite element (FE) models with cohesive damage to assess the strength of external adhesive repaired carbon-fiber reinforced polymers (CFRP) under tensile and compressive loads [2,3,6]. The effect of the shape geometry (single or double strap repair) on the strength of the structure and on the stresses distribution in the repair joint has been particularly studied. They also developed two-dimensional (2D) FE models for bonded repair joints [6,7]. The main conclusion was that the repair strength increases exponentially with the decrease of scarf angle. Gunnion and Herszberg [8] developed 2D and 3D linear elastic parametric finite element models to analyze stresses distribution in the middle of the adhesive joint of CFRP scarf repaired joints under tensile loading. This model allowed obtaining both shear and peeling stresses distribution along the adhesive bondline. A linear geometrical analysis was performed. The investigated parameters included the adhesive and adherend thickness, the scarf angle and the stacking sequence. The main conclusions of their study were the low sensitivity of the adhesive stresses on mismatched adherends lay-ups and the major reduction in peak stresses observed when an over-laminate ply was used to cover the full length of the specimen. Harman and Wang [9] developed an analytical technique to optimize the shape of the scarf joints between dissimilar adherends. Their technique used a linear variation of the scarf angle that generates a characteristic scarf profile for a given adherends modulus ratio. Both analytical and 2D and 3D elastic FE modelling results showed a dependence on the local ply orientation for peel and shear stresses distribution in the adhesive, for different ratios of adherends moduli. Charalambides et al. [10] tested experimentally repaired CFRP joints using a 2°-scarf configuration. Distinct failure

---

* Corresponding author.
E-mail address: Marie-Laure.Dano@gmc.ulaval.ca (M.-L. Dano).

https://doi.org/10.1016/j.ijadhadh.2017.12.008
Accepted 8 December 2017

modes were observed as functions of the environmental conditions (temperature and moisture) and of the load type. They also performed a two-dimensional numerical analysis [11] in order to simulate three different failure modes in scarf repairs: failure in the adhesive layer, failure induced from delamination initiating at the corner of the overlap ply and tensile failure of the composite adherends. Failure loads were compared with previously published experimental work, and the results were found to be in good agreement.

The above-mentioned studies investigated repairs of composite laminates. Several experimental studies and finite element analyses were also carried out to study the behavior of repaired sandwich panels under four-point bending and compressive loads. The repair was either extended across the width of the specimens (2D repair) [12–17] or circular (3D repair) [18,19]. A series of experimental tests were conducted by Tomblin et al. [12,13] to study the effects of different process parameters on the quality of 2D repairs in sandwich panels. A damage tolerance analysis of the sandwich structures was also included in their studies. As an outcome of their work, a methodology for the repair process and the set-up of design tools for damage tolerance analysis of sandwich structures were developed. On the other hand, Mahdi et al. [14–16] used 2D and quasi-3D finite element models to predict the performance of both pristine and sandwich panels with 2D scarf repairs subjected to static and fatigue four-point bending. Failure prediction was based on the first ply failure using the Tsai-Hill criterion for the composite skin but failure of the adhesive was not considered. Numerical analysis results showed a good correlation in terms of stiffness prediction of both undamaged and repaired specimens. However, the predicted ultimate load was problematic and did not show a good correlation with experiment. Ramantani et al. [17] studied also the performance of repaired sandwich panels under four-point bending. They developed a 2D cohesive mixed-modes damage model via interface elements placed along the adhesive bondline. Composite failure was here not considered. For overlap joints, they concluded that the repair strength increases as a function of the overlap length and that the strength increases with lower scarf angles in the case of scarf joints. The compressive behavior of sandwich panels with circular bonded repairs was investigated by Liu et al. [18]. Both experiments and finite element analyses were conducted to study the influence of repair variables such as scarf angle and cure cycle on the quality of the repair. A progressive damage model, based on Hashin criterion for the composite material, was developed and used to predict failure of the repaired sandwich panel. The adhesive film was modeled using cohesive elements. Good correlation between experimental and numerical results was obtained. However, it should be pointed out that since the inner diameter of the repair was small (25 mm) compared to the sandwich panel width (100 mm), the load was by-passed and failure occurred in the parent and not in the adhesive bondline. A very recent study from Zhang et al. [19] was conducted to investigate the mechanical performance of honeycomb sandwich panels with open-hole damage and circular scarf repair under compressive loads. A three-dimensional FE model was developed. Failure criteria based on Hashin criterion with a progressive damage evolution were included for the composite facesheets. The adhesive layer was modeled using cohesive elements and the honeycomb core was considered as an elastic-plastic material. Good agreement was found in terms of ultimate failure load and damage shape between the experimental and numerical results. Failure of the repaired sandwich panel was due to adhesive delamination and patch local buckling. Another finding of this work is that the structure strength increases with the decrease of the scarf angle and that the optimum number of overply layers is one in order to reach the highest strength.

In the above-mentioned research works on sandwich repairs, focus was mainly on scarf-scarf repair and failure of the adhesive film was taken into account using cohesive zone elements. However, in practice stepped-scarf repair configurations are often used for which this modelling technique cannot be applied. Hence, one of the aims of the present study is to account for the effect of the stepped patch on the adhesive peel and shear stresses distribution and strength prediction.

This paper presents one aspect of a larger research program on the repair of sandwich structures [20]. Here, the behavior of co-bonded circular scarf repair of sandwich composite panels under edgewise static compressive and four-point bending loads is studied. Both experimental tests and finite element analyses are performed. First, the repair procedure and the experimental set-up are detailed. Force versus strain curves are presented and a series of failure morphology are shown to determine the failure mode and pattern. Then, the FE models developed using the commercial software Abaqus [21] are presented. Elastic-plastic analysis model with shear failure for the adhesive coupled with the application of a failure criterion for the composite skins is used to predict the ultimate load of the repaired sandwich structure subjected to compressive loading. Finally, the numerical results are compared with experimental results to validate the developed finite element models.

2. Experimental work

2.1. Objective and methodology

An experimental program has been set up to study the mechanical behavior of sandwich panels with a circular flush repair on one of the two facesheets. A flush repair patch was selected over an external repair patch because it offers structural strength as well as an aerodynamically smooth surface. In practice, facesheets in sandwich structures work either in tension, compression or in shear. In this study, only the tensile and compressive behaviors of the repaired facesheet were considered.

To introduce a compressive load in the repaired facesheet, it was chosen to perform a compressive test on the repaired sandwich panel. The test configuration allows having a clear view of the circular repair as it is loaded in compression and digital image correlation systems can therefore be used to measure the strains on the repaired facesheet. To load the repaired facesheet in tension, a four-point bending test was preferred over a tensile test because it is easier to conduct on large specimens and the specimens do not require any special preparation.

2.2. Specimen preparation

The sandwich composite panels used in this work are composed of a Nomex honeycomb core on which two out-of-autoclave four-ply plain weave (PW) carbon-epoxy skins are bonded using a FM300-2M adhesive film. The cured composite ply thickness was approximately 0.19 mm and the film adhesive thickness was 0.25 mm. An over-expanded honeycomb core with a 19 mm thickness was used for the sandwich panels tested in compression. For the sandwich beams tested under four-point bending load, a higher density hexagonal cell core with a 25.4 mm thickness was used to prevent core crushing from occurring. The elastic properties of the composite material, the two Nomex honeycomb cores and the adhesive film are given in Tables 1, 2, 3 and 4, respectively. The inner facesheet, also called the tool facesheet, is a [(+45/−45)/ (0/90)/ (−45/+45)/ (90/0)] quasi-isotropic laminate. The outer facesheet, also called the bag facesheet, has the same lay-up as the inner one. Specimens were tested under edgewise

Table 1
Mechanical properties of the plain weave composite material (CYCOM 5320 T650 PW).

E_{1t} (GPa)	E_{2t} (GPa)	G_{12} (GPa)	ν_{12}	ρ (kg/m^3)
62.7	66.9	4.87	0.047	1500
E_{1c} (GPa)	**E_{2c} (GPa)**	**X_t^1 (MPa)**	**X_c^1 (MPa)**	**X_t^2 (MPa)**
49.3	48.7	999.7	772.2	875.6
X_c^2 (MPa)	**S (MPa)**	**G_{1t} (N mm^{-1})**	**G_{1c} (N mm^{-1})**	**$G_{2t} = G_{2c}$ (N mm^{-1})**
789.7	38	22.5[a]	22.5[a]	22.5[a]

[a] Taken from [23]