Composite Structures 149 (2016) 292–303

Contents lists available at ScienceDirect

Composite Structures

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

Experimental study of compression after impact of asymmetrically tapered composite laminate

Hakim Abdulhamid [a], Christophe Bouvet [a,*], Laurent Michel [a], Jacky Aboissière [b], Clément Minot [b]

[a] Université de Toulouse; INSA, UPS, EMAC, ISAE; ICA (Institut Clément Ader), France
[b] Sogeti High Tech, Aéropark, 3 chemin de Laporte, 31300 Toulouse, France

ARTICLE INFO

Article history:
Received 6 January 2016
Revised 2 April 2016
Accepted 6 April 2016
Available online 12 April 2016

Keywords:
Composite
Ply drop-off
Impact
Compression after impact
Damage tolerance

ABSTRACT

This paper presents an experimental study of CAI (compression after impact) of tapered composite laminate. Two types of layup with thickness changing from 4 mm to 6 mm are considered. A new CAI testing rig, suitable for the specimens and a brief description of impact damage are presented first. Then, the behavior of impacted specimens under compressive loading is discussed along with the effects of ply drop-off parameters (taper angle, ply drop-off disposition and configuration) and impact point location on the failure mechanism. Finally, the residual strength in CAI of tapered laminates is compared with equivalent flat laminates. The results show that compressive behavior of the specimens is mostly governed by a coupling between compression and bending, generated by the discontinuity of the neutral axis in the tapered region. Despite this difference of behavior with flat laminates, the presence of ply drop-off has little effect on the residual strength in CAI.

1. Introduction

Low velocity/low energy impact on composite structure is known to create a large expanse of damage inside the laminate while leaving a barely visible indent on its surface. Such damage reduces the residual strength after impact and especially, its compressive strength [1,2]. In aeronautics, this loss of strength obliges the designer to account for damage tolerance and to use only a portion of the potential of the material. Therefore, understanding the mechanisms that lead to premature failure of the structure is important in order to improve the residual strength of the laminate.

Today, extensive experimental studies of CAI on flat laminates are available in the literature. Apart from measuring the residual strength, authors investigated the influences of many parameters like the resin [3,4], the staking sequence [5,6] and the transverse reinforcement [7–9]. Others focus on the study of failure mechanisms during CAI and identified three major mechanisms: buckling, propagation of delamination and fiber failure. The majority of authors agree that buckling or local buckling leads to premature failure of the laminates [5,10–13]. In fact, the delamination created during impact divides the plate into multiple sub-laminates. Since the buckling strength of a sub-laminate is lower compared to the initial plate, buckling or local-buckling is likely to happen during CAI. In some cases [4,9,14], the buckling induces some propagation of delamination before the plate total failure. However, the delamination does not necessary lead to total collapse of the specimen since its initial propagation does not reach the lateral edges. Furthermore, some authors [15–17] observed some propagation of compressive fiber failure going from the impact area. This crack propagation can be induced by buckling or local stress concentration and in some cases leads to the final collapse of the specimen. In summary, failure in CAI of flat laminate is due to multiple mechanisms and some coupling can be involved between them. Those different studies highlighted the complexity of the phenomena, yet, they have permitted a reasonable understanding of the CAI behavior of flat laminates.

Regarding the tapered laminates, according to the authors' knowledge, there is no related detailed study of their CAI. The majority of authors deal with their static [18–20] or fatigue [21,22] strength. For example, by means of Moiré interferometry, Xing et al. [18] studied the failure mechanism at the toe and the knee of the resin pocket under tensile and compressive loadings. Steeves and Fleck [19] investigated the influences of interlaminar delamination and fiber micro-buckling on the compression strength of tapered laminates. Weiss et al. [22] studied the influence of ply drop-off location with regards to the initiation of delamination in fatigue. Few authors performed impact studies of

* Corresponding author at: ISAE (Institut Supérieur de l'Aéronautique et de l'Espace), 10, avenue Edouard Belin, BP 54032, 31055 Toulouse Cedex 4, France.
E-mail address: christophe.bouvet@isae.fr (C. Bouvet).

http://dx.doi.org/10.1016/j.compstruct.2016.04.015
0263-8223/

tapered laminates. Greenhald et al. [23] conducted a detailed comparison of impact study at the stringer foot and bay of a stiffened panel. It is found that the ply drop-off represented by the stringer foot modifies the local bending stiffness of the laminate. The propagation of damage is less important at the stringer foot compared to the damage created by an impact at the bay. Kairouz and Ball [24] investigated the impact performance of non-crimp fabric composite material with an internally dropped-off ply. They recorded a loss of 20% of the damage initiation threshold force compared to plain laminates.

The effects of ply drop-off on the CAI strength and failure mechanisms have not been studied and need to be investigated since those particular areas can also be subjected to impact in an aircraft structure.

Impact and CAI strength are material and structural related properties. For this reason, the specimen size and tests boundary conditions influence the results. The majority of available studies follow industrial standards like (BSS7260 [25] or AITM1-0010 [26]). The standards are quite similar and were defined to predict the CAI strength of a monolithic flat panel. It is only recently that international standards (ASTM7136 and ASTM7137 [27,28]) are available for the tests. However, there is still no standard for the study of impact and CAI of asymmetrically tapered composite panel. Therefore, new dimensions of specimens and boundary conditions need to be defined.

This study continues an ongoing research on the impact damage tolerance of tapered laminates. The first part of it, characterizing the impact damage is available in [29]. This paper is devoted to the analysis of the behavior and residual strength under compressive loading of impacted specimens with ply drop-off. After the presentation of specimens features, a new boundary condition for CAI test of asymmetrically tapered laminate is introduced and validated. Then, the behavior in CAI of tapered specimens is described considering the effect of impact point location and face. Next, the failure mechanism in CAI is studied. And finally, the residual strength in compression of tapered laminates is compared with that of the flat ones.

2. Experimental Setup

2.1. Specimens and tests boundary conditions

Two types of layup, A and B, presented in Table 1 are considered in this study. Both layups have the same thickness range. For A (B) specimen, the thickness of the thick section is 6 (6.25) mm and that of the thin section is 4 (4) mm. The main difference between both layups is in the number of inter-laminar interfaces. For layup A, the number is reduced by grouping in pairs the plies of the same orientation. For layup B, plies are more distributed through the thickness, therefore, increasing the number of interfaces compared to A. Fig. 1 illustrates the layup of A and B tapered specimens and the ordering of the dropped-off plies in the tapered area. Two versions of B (B^1 and B^2) are considered by changing the ordering of dropped-off plies. Also for A, the dropped-off groups of plies are terminated whether in staggered (A^{st}) or simultaneous (A^{si}) way. The consistency of the spacing is ensured with a microscopic screw driven ruler during layup. For A^{si} and B^1 and B^2 layups, two tapering angles are used: a steep one with 1.5 mm spacing per 0.25 mm ply thickness and a smooth one with a spacing of 2.5 mm and a spacing of 1.5 mm is used in A^{st} specimens. Additionally, flat

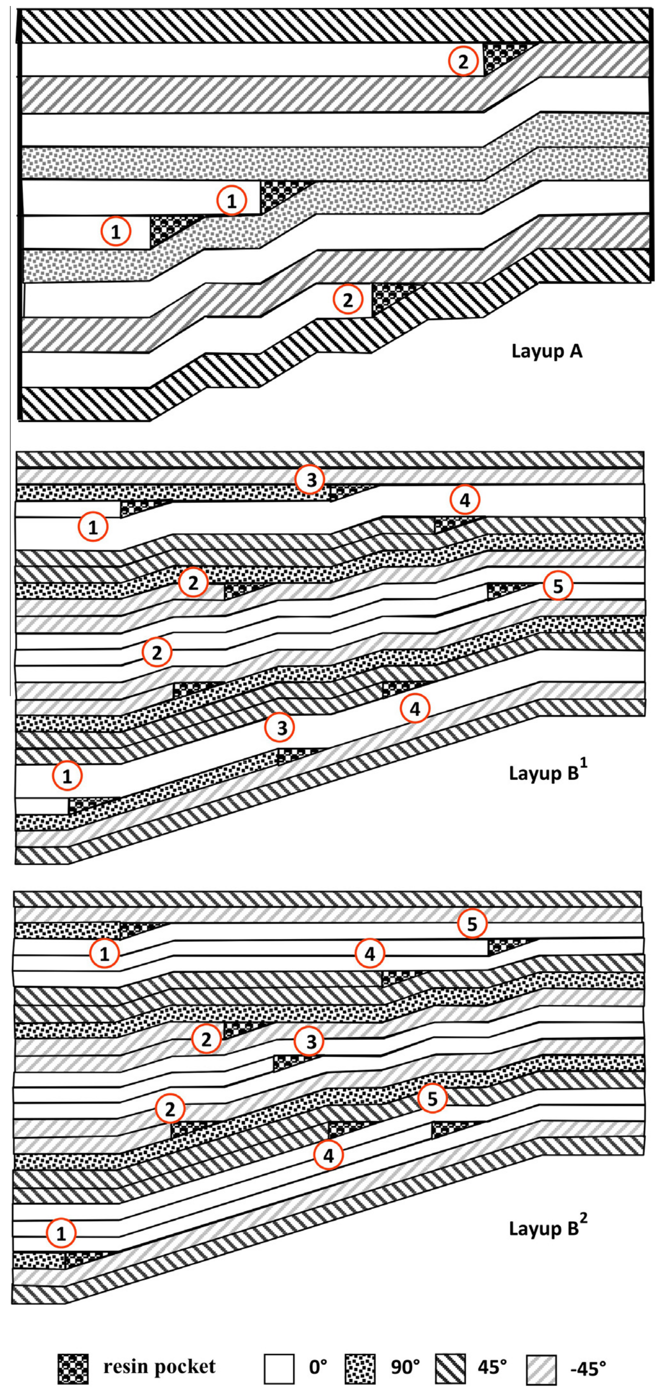

Fig. 1. Layup profile and ply drop-off ordering of layups A, B^1 and B^2 specimens.

Table 1
Definition of layup of the specimens.

Layup A	$[45_2$	0_2	-45_2	0_2	90_2	$0_2]_s$							
Termination order	–	2nd	–	–	–	1st							
Layup B	[45	−45	90	0	0	0	45	45	90	−45	−45	0	$0_{1/2}]_s$
Termination order for B^1	–	–	3rd	1st	–	–	4th	–	–	2nd	–	–	5th
Termination order for B^2	–	–	1st	5th	–	–	4th	–	–	2nd	–	–	3rd