Composite Structures 184 (2018) 198–210

Contents lists available at ScienceDirect

Composite Structures

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

Effect of stiffener damage caused by low velocity impact on compressive buckling and failure modes of T-stiffened composite panels

Wei Sun[a], Zhidong Guan[a,*], Tian Ouyang[a], Riming Tan[a], Xiaodan Zhong[b]

[a] *Department of Aircraft Design, Beihang University, Beijing 100191, PR China*
[b] *Shenyang Aircraft Design and Research Institute, Shenyang 110035, PR China*

ARTICLE INFO

Keywords:
Stiffened composite panel
Low velocity impact
Stiffener damage
Debonding
Compression after impact
Buckling

ABSTRACT

Effect of stiffener damage caused by Low Velocity Impact (LVI) on compressive buckling and failure load of the three T-stiffened composite panel was studied by experiment in this paper. Stiffener damages were introduced at four impact energy levels with the impact position located on the panel side over the middle stiffener. The impact experimental results show that the impact energy inducing the initial damage of the stiffened panel is about 34 J. With the increase of impact energy, the damage of the panel is slighter than Barely Visible Impact Damage (BVID), while the stiffener damage and stiffener/panel debonding are serious. The panel dent will not be visible until the stiffener is completely fractured under a higher energy impact. Compression after Impact (CAI) experimental results show that although the initial compression stiffness of the stiffened panel is not affected by the stiffener damage, the compressive stiffness decreases with the increase of compressive load due to the damage propagation of the impacted stiffener and buckling of panel. The failure loads decrease significantly when the damage of stiffener and the stiffener/panel debonding occur as the result of LVI, with a maximum drop of 44% compared to the undamaged specimen.

1. Introduction

Composite materials have been widely used in the fields of aeronautics and astronautics for their well design, high strength/weight and stiffness/weight ratio. For aircraft structures, thin-walled components such as composite stiffened panels have been extensively applied because of their excellent bearing capacity and post-buckling behavior [1–6].

However, due to the defects of the impact damage resistance of the composite materials, serious inter-laminar and intra-laminar damage will be induced by low velocity impact. The mechanical response of low velocity impact on composite laminates have been extensively studied using experimental and numerical methods [7–11]. Aymerich et al. [12] studied the impact damage of composite laminates by experiment and numerical simulation. Their results show that damage of the laminates induced by low energy impact mainly includes matrix cracking and inter-laminar delamination. The Puck initial failure criteria combined with Continuum Damage Mechanics (CDM) was used by Chen [13] to predict the low velocity impact response of composite laminates, and Cohesive Zone Model (CZM) based FEM was employed to simulate the inter-laminar delamination.

For composite laminates, Barely Visible Impact Damage (BVID) is used to evaluate the impact damage because it can be effectively visually detected. In aeronautical standards, the threshold of detectability after a few days of rest and humidity aging is 0.3 mm of dent depth [14]. In order to predict the impact permanent indentation, Bouvet [15] elaborated a numerical model to simulate the different impact damage types developing during low velocity/low energy impact. He [16] proposed a method for predicting the impact permanent indentation of composite laminates in consideration of the elastoplastic constitutive of the composite materials. The results show that the fiber breakage and material anisotropic plasticity are the two main factors in the formation of the impact crater. Fanteria [17] put forward a new non-linear constitutive model for in-plane and out-of-plane intra-laminar shear in composite materials. The impact response and permanent indentations of laminates were simulated by this model, which are in good agreement with the experiments. In present study, the BVID is taken as 1.0 mm which was immediately measured after impact test.

It has been found that there is a connection between the residual strength of composite laminates and BVID due to the serious damages, such as fiber fracture, matrix cracks and inter-laminar delamination, inside the laminates. These damages significantly reduce the load carrying capacity of the composite laminates [18–21]. For stiffened composite panels, BVID caused by low velocity impact can also dramatically

---

[*] Corresponding author.
E-mail address: d5062010@163.com (Z. Guan).

http://dx.doi.org/10.1016/j.compstruct.2017.09.084
Received 18 May 2017; Received in revised form 12 August 2017; Accepted 26 September 2017

reduce the compressive strength. The effects of impact damage underneath the stiffener edge on compressive buckling and ultimate strength of stiffened panels were studied by experiment and FEM simulation [22]. Feng [23] investigated the effect of different impact damage positions on the buckling and post-buckling behaviors of stiffened composite panels. The results show that the compressive buckling load and failure load with different impact positions are nearly unchanged. The present author holds that it may be the damage introduced in their study too slight to affect the failure modes.

Low velocity impact on the free edge of the composite stiffener was studied by Li [24,25] and Ostre [26]. The stiffener edge impact damage was considered as a critical factor on the loss of compression strength. Suh [27] investigated the compression after impact strength of stiffened composite panels with clearly impact damage in a stiffener. The stiffened panels were impacted with 30 J from the skin side over the stiffener, and significant stiffener damage was observed. In addition, Raimondo [28] and Orifici [29] focused on the skin-stringer debonding growth in stiffened composite panels subjected to compressive load.

To the author's knowledge, the effect of the stiffener damage caused by low velocity impact on the residual strength of composite stiffened panels is seldom studied, especially when the impact position is located on the panel side over the stiffener (see in Fig. 1). Experimental results show that the stiffener damage occurs first with the panel dent lower than BVID under stiffener impact, and the impact dent is not significant until the stiffener is completely broken with the increase of impact energy. Therefore, using BVID of the panel to evaluate the impact damage is not suitable any more. Stiffener impact is considered as a critical factor on the loss of compression strength. It is necessary to analyze the relationship between the BVID and the compressive residual strength of stiffened composite panels.

In this paper, the effect of damage induced by stiffener impact on the compressive behavior of three T-stiffened composite panels was studied. There are two main objectives in the present paper, 1) the damage of the stiffened panels caused by stiffener back impact; 2) the effect of stiffener damage on compressive buckling and failure modes. The main contents of this paper are as follow: in Section 2, the impact and CAI experiments are described in detail; in Section 3 and 4, the impact and CAI test results are analyzed respectively; in Sections 5, some conclusions are obtained.

2. Experimental description

2.1. Specimen

As the Fig. 2a shows, the specimen is a flat panel stiffened by three stiffeners with T-shaped cross section along the longitudinal direction, and both longitudinal ends of the stiffened panel are reinforced by epoxy resin blocks with steel frames on the periphery. Regardless of the reinforced blocks, the length (L) and width (W) of the panel are 300 mm and 230 mm respectively, and the thickness of the panel is 3 mm. The spacing between each T-shaped stiffener is 77 mm. Detailed dimensions are illustrated in Fig. 2b.

The T-shaped stiffener consisted of three parts, two L-shaped components with the thickness of 1.56 mm and a 0.48 mm-thick Transition Layer (TL) between the stiffener and the panel. The triangular space of stiffener was filled by the UD composite (see in Fig. 2b). Specimens were made of UD carbon fiber/epoxy resin T300/QY8911 prepreg with the thickness of 0.12 mm. Material parameters are shown in Table 1.

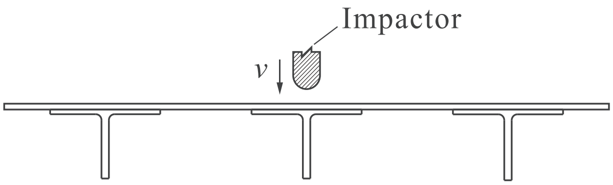

Fig. 1. Schematic diagram of stiffener impact (the impact position locate in the middle section).

Stacking sequences of each specimen are presented as follow: the panel consisted of 25 laminas with a stacking sequence of $[45,-45,0,-45,45,0,-45,45,90,45,-45,45,\bar{0}]_s$, while the L-shape component of the stiffener was composed of a 13 laminas with a lay-up sequence of $[45,-45,0,0,-45,45,0,0,90,0,0,45,-45]$, and the stacking sequence of transition layer was $[45,-45,0,0]$.

2.2. Impact experiments

A vertical drop-weight impact test system was used to introduce the impact damage, as shown in Fig. 3. Different impact energy levels were set in the impact test by adjusting the height h of the impactor. A photoelectric sensor was used to accurately measure the initial impact velocity v_0 and the rebound velocity v_b. The expressions of impact energy E_I and absorbed energy E_a are as follow:

$$E_I = mgh = \frac{1}{2}mv_0^2 \tag{1}$$

$$E_a = \frac{1}{2}m(v_0^2 - v_b^2) \tag{2}$$

In order to obtain the contact force-time response, a force sensor was employed to record the contact force vs time curve.

The stiffened panels were placed on the test platform for the introduction of impact damage without boundary constraint. The impact point was located on the back of the middle stiffener. Four impact energy levels (35 J, 42 J, 50 J and 85 J) were used, and the specimens corresponded to them were labeled as S1, S2, S3 and S4 respectively. The diameter of the impactor, manufactured from steel, was selected 12.7 mm. According to ASTM D7136 [30] recommendation, the total mass of the impactor should be 5.5 ± 0.25 kg, thus a 5.477 kg impactor was used in the present experiments.

2.3. CAI experiments

The compression after stiffener impact tests were carried out on MTS material testing machine, of which the maximum load is ± 500 kN. Strain gauges were pasted on the surface of each specimen to obtain the strain response during the compression process. The back-to-back distribution of the strain gauges is shown in Fig. 4a. The strain gauges on the panel side were marked as (G)i(i = 1–28) while on the opposite side were marked as (G)0i. In addition, the strain gauges on the web were marked as F j and F0 j(j = 1–12).

The stiffened panels were placed on the rigid platform for axial compression tests, and the compressive displacements of specimens were obtained by a displacement meter (see in Fig. 4b). A small load about 4 kN was used as the initial load on purpose to eliminate the nonlinear effect of the load-displacement curve when the axial compression load was low. Continuous loading and data acquisition methods were employed. The axial compression loading rate was 30 kN/min, and the sampling frequency of the load and strain were both 2 HZ.

3. Impact results and discussions

3.1. Contact force response

The contact force response in the low velocity impact test can reflect the damage characteristics of the composite structures. For composite laminates, a sudden drop of contact force occurs due to specimen stiffness loss as a result of inter-laminar damage [31]. In addition, the contact force response of stiffened composite panels under low velocity impact was studied by Found [32] and Li [33]. In present study, the contact force-time curves of the specimens at different impact energy