Composite Structures 134 (2015) 18–26

Contents lists available at ScienceDirect

Composite Structures

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

Low-velocity impact response of composite laminates with steel and elastomer protective layer

D. Düring [a,*], L. Weiß [a], D. Stefaniak [a], N. Jordan [b], C. Hühne [a]

[a] DLR – German Aerospace Center – Institute of Composite Structures and Adaptive Systems, Lilienthalplatz 7, 38108 Braunschweig, Germany
[b] Airbus Operations GmbH, Airbus-Allee 1, 28199 Bremen, Germany

ARTICLE INFO

Article history:
Available online 6 August 2015

Keywords:
Hybrid composite
Laminate
Impact behaviour
Low-velocity impact
FML

ABSTRACT

In the presented study the response of a carbon-glass composite/steel/(elastomer) multi-material structure to low-velocity impact was investigated experimentally. Two different steel layer thicknesses, 0.125 mm and 0.25 mm, as well as the addition of a rubber layer were assessed regarding their influence on internal and external damage, the absorbed energy, force evolution, and deformation.

It was found that the doubling of the steel layer thickness stiffens the structure marginally and induces deeper indentations but has no significant influence on the absorbed energy or the damage threshold F_D. The additional rubber layer increases the damage threshold load. Below this threshold, the response is dominated by global, elastic deformation decreasing internal and external damage and thereby the amount of absorbed energy. Above F_D, large local deformations around the centre of impact lead to a more critical surface damage which dissipate a part of the energy decreasing the extend of delaminations.

1. Introduction

The application of Carbon-Fiber Reinforced Plastics (CFRPs) as structural materials has been established in the aerospace industry in the past decades due to their high stiffness and strength combined with a relatively low density. Especially in aeronautical applications, those structural components are subject to impact by rain, sand, and hail [1–3]. One major problem is the weak erosion resistance of composite materials [4–7]. In addition, the impact of larger objects such as hail stones, maintenance tools or runway debris can cause serious damage to the CFRP structure.

Generally, a distinction is made between low-velocity and high-velocity impacts but expert opinions differ regarding the classification [8]. For example, according to Sjöblom et al. [9] and Shivakumar et al. [10] low-velocity impacts can be regarded as quasi-static events. The contact time between impactor and laminate is long enough for the entire structure to respond which causes intralaminar and interlaminar failure. Consequently, the actual impact velocity depends on the target and impactor properties and can reach up to multiple 10 m/s for low-velocity impact. Olsson expands this idea and states that the impact type should not be distinguished by the impact velocity, but by the type of impact response which depends on the impactor to plate mass-ratio [11]. However, Cantwell and Morton [12] and Abrate [13] define the exact threshold of 10 m/s between low- and high-velocity impact. In this study impacts tests with velocities < 5m/s and masses up to 6 kg were conducted. In accordance with the literature outlined above, the executed tests were classified as low-velocity large-mass impacts.

Insidiously, those quasi-static impacts may cause significant internal damage in composite structures without being detectable by visual inspection [9]. For the sake of clarity, a threshold value for a barely visible impact damage (BVID) is defined as damage visible within 1 m distance. The demanding detectability coupled with a significant reduction of the mechanical properties require a certain damage tolerance of the structure being insusceptible to given load levels within certain inspection intervals [8,14].

With the growing number of air travel, the reduction of CO_2 emission has become a central concern in the aircraft industry. Latest developments focus on the reduction of aerodynamic drag through laminar flow control, whereby a distinction is made between natural, hybrid, and full laminar flow control [15]. In order to obtain natural laminar flow, the airfoil is specially formed to smoothly accelerate the flow over the surface. Erosion and indentations from impact of larger objects, even if barely visible, can damage the surface causing a disturbance of the laminar flow. Crucial factors are, in addition to the Reynolds number, the diameter d, the dent depth h, and the ratio h/d [16,17]. The Reynolds number and the dent diameter are hardly influenceable, wherefore

* Corresponding author. Tel.: +49 5312953186.
E-mail address: denise.duering@dlr.de (D. Düring).

http://dx.doi.org/10.1016/j.compstruct.2015.08.001
0263-8223/

the dent depth after impact is to be kept to a minimum by structural or material based modifications.

Since there is no single material that meets the mentioned requirements, a combination of different materials with various favourable properties shall resist the damage caused by erosion and impact. Stainless steel shows an erosion resistance which is at least one order of magnitude higher than CFRP surfaces [6].

The hybridisation of CFRP laminates with thin metal foils, resulting in so-called fibre-metal-laminates (FMLs), can increase the residual strength after impact and impact resistance substantially [18,19]. Stefaniak et al. proved an increased residual strength especially for FMLs containing thin steel foils [20].

Another approach is to improve the impact resistance by modification of the epoxy resin with rubber [21,22]. However, Sarlin et al. [23,24] presented a hybrid structure in which rubber is utilised as adhesive material between a steel layer and the composite material to avoid the drawbacks of surface treatment. They investigated damping properties and the high-velocity impact behaviour and discovered that the additional rubber layer absorbs the impact energy and decreases internal damage.

The purpose of the present study was to investigate the suitability of an additional elastomer layer and different top layer thicknesses for a composite wing leading edge fulfilling natural laminar flow (NLF) requirements under eroding conditions and impact events. Since laminarity of the surface, and therefore the smoothest possible surface is essential for the subsequent application, one objective was to determine whether the surface susceptibility to impact events can be decreased by the stacking modification. Smaller impact damages result in a poorer detectability, wherefore a further objective was to increase the damage tolerance of the CFRP structure by a reduction of delaminations.

Three different hybrid laminates were analysed regarding their low-velocity impact resistance. For erosion protection, one single steel foil layer was located on the surface of the structure. In new aircraft models the surface of the wing leading edge is heated by a resistance heating [25]. In order to achieve the necessary comparability, a conductive heating system, consisting of a CFRP layer insulated by Glass-Fiber Reinforced Plastic (GFRP), was applied beneath the steel layer. In order to avoid heat insulation towards the surface, the rubber layer, which is supposed to improve impact resistance, was not located directly underneath the steel layer. Instead, it was applied between heating and underlying CFRP-structure, which results in a different hybrid configuration with respect to the configurations investigated by Sarlin et al. [24]. The influence of the additional rubber layer and the thickness of the steel layer on the low-velocity impact resistance were investigated. Afterwards, the internal and the external damage as well as the energy absorption were compared.

The aim of this study is not the development of an analytical model but a test-based experimental investigation which provides a basis for creating such a model.

2. Experimental

2.1. Materials

Three different hybrid specimen configurations were investigated. Table 1 shows their constituents as well as their thicknesses and short designations. All specimens contained an 18-ply quasi-isotropic CFRP layup: $[\pm 45/0/\pm 45/90/\pm 45/(0)_2/\pm 45/90]_S$ with an overall nominal thickness of 5.13 mm. The unidirectional and woven prepreg with a MTM44–1 matrix (Cytec) were laid up manually. On the CFRP backing material the conductive heating was applied, consisting of a woven CFRP-ply surrounded by two GFPR-layers on top and bottom for electrical insulation. The details for both CFRP and GFRP materials are provided in Table 2. Between the heating and the CFRP-core lied the optional rubber layer which was an Ethylene Propylene Diene Monomer (EPDM) manufactured by the Kraiburg GmbH, Germany, with a nominal ply thickness of 0.5 mm. The surface layer above the heating was a stainless steel X10CrNi18–8 of which two different thicknesses, 0.125 mm and 0.250 mm, were investigated. The steel foils were manually roughened on the joining surface by grinding (Grade 180) and then treated in a sol–gel process as described in [20]. Fig. 1 shows the schematic layup. The hybrid structure was finally cured following supplier recommendation for MTM44–1 [26].

Table 1
Tested sample configurations, *DB = direct bonded without elastomer layer, **EL = with additional elastomer layer.

No.	Nominal steel thickness	EPDM	Nominal specimen thickness	Designation
1	0.125 mm	no	5.977 mm	S125-DB*
2	0.125 mm	yes	6.477 mm	S125-EL**
3	0.250 mm	no	6.102 mm	S250-DB*

2.2. Experimental methodology

A CEAST Fractovis drop weight tower was used to conduct the low velocity impact tests. Four rubber clamps fixed the 100 mm × 150 mm size specimens over a flat support with a 75 mm × 125 mm rectangular cut-out according to ASTM D7136 [27]. The samples were impacted once by a steel indentor with a hemispherical tip (diameter = 20 mm) which contained a 20 kN piezo-electric load cell. In combination with an acceleration sensor the actual impact energy as well as impactor displacement and impact velocity were verified. The impact energy ranged from 9 J to 50 J whereby the respective energy was set by the combination of weight and drop height. Hence, the measured impact velocity varied between 3.0 m/s and 4.1 m/s with very small standard deviations. Table 3 summarises the tested energies with the corresponding masses and measured velocities. Each configuration was tested three times ($v1$, $v2$, $v3$) at all five analysed energies whereby the study is based on the investigation of 45 samples in total.

Table 2
CFRP and GFRP material properties.

Material	Fiber type	Nominal ply thickness
CFRP-UD	IMS65	0.255 mm
CFRP-woven	CF5804A	0.322 mm
GFRP-woven	GF0903	0.101 mm

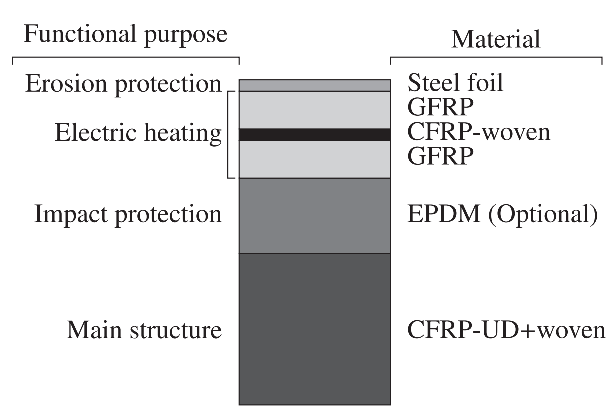

Fig. 1. Schematic sample layup. Dimensions not to scale.