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High velocity impact on preloaded composite plates

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ABSTRACT

An experimental and numerical study of the influence of tensile and compressive preloading on the high velocity impact performance of T800S/M21 carbon/epoxy plates was conducted. Gas gun tests with spherical hard body projectiles were used to generate impact damages under five different states of preloading and five different velocities in the range of 50–90 m/s. Ultrasonic C-scans and micrographs were used for the post-test damage inspection, where matrix cracking and delaminations were observed as the major impact damage modes. Tensile preloading was found to reduce the extent of delaminations, while compressive preload led to an increased extent of delaminations resulting from a higher bending deflection of the plate under impact. State-of-the-art impact simulation methods in Abaqus/Explicit with Hashin failure criteria for the composite material and cohesive elements for delamination interfaces were capable of representing these effects of preloading that were observed in the experiment. This study shows that preloading has an influence on the impact response of laminated composite plates and should be considered in relevant vulnerability analyses.

1. Introduction

Carbon fibre-reinforced composites are known for their high weight-specific stiffness and strength properties, which make them a preferred candidate in the material selection for modern lightweight structures in aeronautic and automotive engineering. However, at the same time, they are known for their vulnerability against impact loads, which can cause internal damage like delaminations or matrix cracks that can reduce stiffness and strength and grow under load.

Therefore, the impact response of composites has been studied by numerous researchers in the past and uncountable publications on this topic can be found. Most of these investigations focus on composite laminates that are unloaded before impact. This can be adequate for academic studies of general mechanical phenomena happening under impact, but may be insufficient e.g. for the investigation of the impact performance of structural aircraft parts in flight, which are typically under a state of prestress before impact. For example, the lower aircraft fuselage panels are typically exposed to compressive loads during take-off, when the impact from a stone – propelled by the tires – is likely to occur. There is a strong interest in investigating the influence of preloads on the impact response of composite structures.

Most published studies on this topic are based on low velocity impact loads with relatively high masses and low impact velocities involved, which shall represent e.g. the scenario of tool drop during maintenance. Such loads can experimentally be achieved on a drop tower test rig with a falling mass impacting the preloaded sample [1–3] or using an instrumented pendulum test rig [4–6]. During such tests, the investigation of tensile preloads is comparably easy to perform and has been conducted in [7–16]. Compressive preloads, in contrast, introduce the complexity of plate buckling, which was analysed in [17–19]. Analytical studies of the low velocity impact response of composite plates under compressive and tensile preload are presented in [20–23].

More critical for most composite structures in aeronautics are high velocity impact loads from scenarios like hail impact or runway debris impact, involving comparably small masses and high impact velocities. The high velocity impact response of preloaded laminated composites was investigated in only very few studies. For this purpose, a gas gun is typically used, which accelerates the projectile to velocities of approx. 50–300 m/s. In [24] a 13 mm steel sphere was fired with velocities from 20 m/s to 70 m/s against a 2 mm carbon fibre/epoxy plate with tensile preload leading to a change in damage pattern for higher preloads. A study of the high velocity impact response of 2.1 mm thick composite plates under tensile preload using a 21 g glass sphere projectile and an impact velocity of 64 m/s is presented in [25], where less delaminations compared to the unloaded case were obtained under tensile preloads. Ballistic impact tests on 4.5 mm thick woven E-glass/vinyl ester plates with compressive preload and velocities roughly in the range of 100–300 m/s were performed in [26]. The authors report a detrimental effect on the residual

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strength of the composite plate. Further ballistic impact tests on 3.19 mm thick woven E-glass/polyester plates with biaxial tensile preload were performed in [27,28], using a 7.5 mm steel sphere and velocities from 140 m/s to 525 m/s. An increase of the ballistic limit for the preloaded plates is reported, correlating to their analytical and numerical results. The influence of tensile and compressive preloads on the soft body impact behaviour of composite laminates has been studied experimentally and numerically in [29]. A gelatine projectile was used during these tests as a substitute material for bird strike loading. Preloading showed to have an effect on global plate bending deformation and extent of damage.

The aim of the current study was to experimentally assess the influence of compressive and tensile preloading on the hard body impact response of carbon fibre/epoxy composite laminates. Using two different preload levels under compression and tension in addition to the unloaded case, a total of five different preloading scenarios and a range of five different velocities are covered in order to obtain a large experimental database. Ultrasonic C-scans and micrographs were used to evaluate in detail the individual states of damage. The second aim of this study was to investigate if state-of-the-art finite element modelling methods of composite laminates are able to predict the effect of preloads in a comparable manner like in the experiments and if further information on the mechanical behaviour under impact loading can be drawn from the numerical results, which could not be measured during the test.

2. Materials and manufacturing

The composite plates used for the high velocity impact tests were made from 17 plies of Hexcel T800S/M21/UD134 toughened carbon fibre/epoxy prepreg with a stacking sequence of [+45°/90°/−45°/0°/+45°/−45°/0°/0°/90°/0°/0°/−45°/+45°/0°/−45°/90°/+45°] and a nominal thickness of 2.125 mm. The micrograph in Fig. 1 shows a cross-section of the laminate with the dark areas between the plies not being cracks or manufacturing imperfections but conglomerations of thermoplastic interleaf particles of the toughened resin system for enhanced impact damage tolerance. The plates were cured in an autoclave at 180 °C and 7 bar pressure for 120 min. Standard coupon tests of this material were performed as part of the test campaign in order to obtain the elastic, strength and damage properties that are necessary for the numerical material modelling.

The final specimens for the impact tests had a size of 550 mm × 200 mm with bonded metallic end tabs of 125 mm length for the fixation in the preloading device, reducing the free specimen length to 300 mm × 200 mm (Fig. 2). A total of six strain gauges were used for the plates with compressive preload in order to accurately determine the level of prestrain and the buckling pattern. Three strain gauges were used for the plates with tensile preload or without preload.

3. Experimental testing

3.1. High velocity impact test conditions

The high velocity impact tests were performed with a gas gun and a specially designed test rig that allows for uniaxial tensile or compressive preloading of the composite plate specimens. The longitudinal ends with the metallic end tabs were clamped to the test rig, the lateral ends were simply supported at the front and back surface via rounded steel supports providing a linear contact located 10 mm from the plate's lateral edges. These supports restrict any translation of the plate along its normal direction but enable its rotation along the plate's length axis.

Two different hard body projectiles of spherical shape were used in this test campaign. First tests were performed with a steel ball with a diameter of 30 mm and a mass of 110 g. However, even for the lowest velocities that can be obtained on this gas gun of approx. 50 m/s, full penetration occurred, which was not useful for a detailed analysis of impact damage as a function of impact velocity (Fig. 3a). Therefore, all the following tests were performed with a glass marble with a diameter of 25 mm and a mass of 21 g (Fig. 3b). With its mechanical properties the glass projectile is representative of blunt impactors such as stones or runway debris and ensures reproducible results since it does not fracture upon impact. The glass marble behaves elastically during impact without any cracking and the same projectile could be used for all tests without any damage.

Five different impact velocities in the range of 49–92 m/s or kinetic energies in the range of 25–80 J were tested with the projectile impacting the plate centre. Furthermore, five different preloading conditions were applied:

- Tensile prestrain of 0.25%, which is a typical value for the limit load of this structure (related tensile force 84 kN).
- Tensile prestrain of 0.10% for only few specimens (related tensile force 34 kN).
- Unloaded.
- Compressive preload of 19 kN, which is 1.43 times higher than the experimentally determined buckling load and represents the limit load for this structure (only few specimens).
- Compressive preload of 28 kN, which is 2.15 times higher than the experimentally determined buckling load and represents the ultimate load for this structure.

A differentiation for tensile and compressive preloading in terms of strain or force levels was made here as limit loads and ultimate loads in aircraft engineering are typically given as strain values for the tensile load case and as a relation to the buckling load for the compressive load case. Plate buckling leads to an

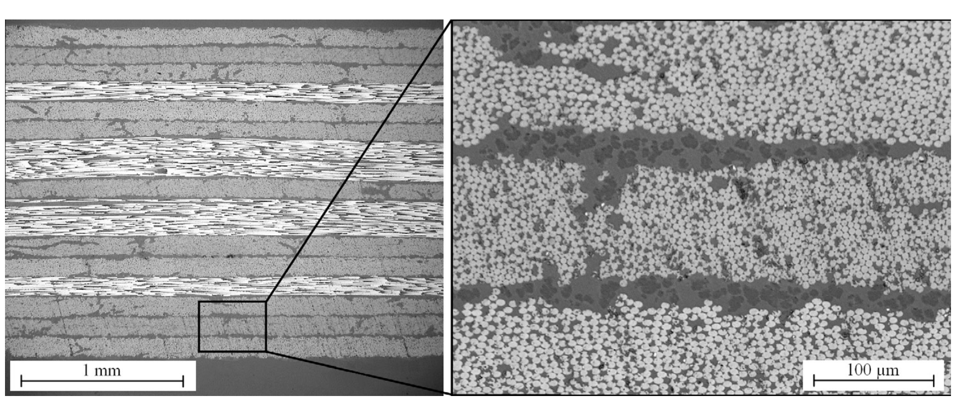

Fig. 1. Micrograph of T800S/M21 laminate with thermoplastic interleaf in M21 epoxy resin.