EXPERIMENTAL STUDY OF DAMAGE TOLERANCE IN PRE-STRESSED COMPOSITE PANELS UNDER GAS GUN IMPACT

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Abstract

The paper describes a gas gun impact test programme on pre-loaded composite panels, where two impact scenarios are considered: Notch damage from 12 mm steel cube projectiles, and blunt impact damage from glass balls. The influence of preload and impact damage on residual strengths are studied. Tests show very good structural integrity for composite panels in tension and compression under notch impact damage, with no significant reduction in strength due to pre-loading. However, blunt impact tests lead to large delamination damage regions, reducing compression strength in buckling, which is intensified by compression pre-load.

1 Introduction

A critical safety issue for the design of primary aircraft structures is vulnerability and damage tolerance due to foreign object impact from bird strike, hail, tyre rubber and metal fragments. The damage tolerance strategy for the aircraft industry is based on defining critical damage states for composites which are linked to damage visibility and hence damage detection during service. The paper describes an experimental damage tolerance study carried out for EASA on the 'Significance of Load upon Impact Behaviour of Composite Structure' (LIBCOS [1]). Currently impact tests on aircraft structures are carried out on test specimens supported in a test fixture in a stress-free condition. However aircraft fuselage and wing structures in flight are subjected to quasi-static loads up to design limit load, hence foreign object impacts usually occur on preloaded structures which may influence damage tolerance. LIBCOS studies experimentally the effect of preloads on impact damage in carbon/epoxy structures, and on subsequent residual strengths of damaged structures. There have been a number of experimental studies on influence of preload on impact response of composite plates and structural elements, [2] - [6]. Most previous studies are based on low velocity drop tower tests, more relevant to BVID damage, and not strictly relevant to Category 4 discrete source impact damage from bird strike, metal fragments etc. The work shows interaction effects between preload and impact damage, but is not systematic enough to provide clear guidelines for improving aviation safety requirements. This motivates the present study of gas gun impact tests on composite plates, representing an idealised fuselage bay or wing panel, which are preloaded in either tension or compression at strain levels typical of aircraft design limit loads (DLL).

2 Materials and test procedures

2.1 Plate specimen

The UD carbon/epoxy prepreg Cycom 977-2-35-12KHTS-134-300, a typical industry standard composite material from civil transport aircraft, was used to manufacture the composite panels used in the test programme. Two generic laminate layups were selected as indicated in Table 1. These are Lam. A, a symmetric 17 ply layup with nominal thickness 2.125 mm for the tension loaded panels and Lam. B a 25 ply lay-up with thickness 3.125 mm for the compression loaded panels. The layup notation in the table indicates the % of plies in the (0°/±45°/90°) directions to the plate long axis.

Lam.	Thickness [mm]	Lay-up	Application
A	2,125	17 UD plies (35/47/18)	Tensile pre-loads
B	3,125	25 UD plies (40/48/12)	Compression preloads

Table 1. Lay-up of the tested composite panels

For a transport aircraft composite fuselage, a typical frame pitch is considered to be in the range 530 mm – 635 mm, with stringer spacing in the range 130 mm - 200 mm. For the test programme, a basic plate geometry of 500 mm x 200 mm was selected as standard.

2.2 Test methodology

2.2.1 High velocity impact tests

At the DLR Institute of Structures and Design, a pre-stressing fixture was upgraded as shown in Fig. 1b for applying pre-stressing under compression or tension. A hydraulic cylinder jack is used to apply the pre-stressing loads (max. 1000 kN) under load control. Depending on its location and mode of operation, compression or tension loads may be applied. The test fixture is mounted on 4 adjustable feet, which enable the point of impact on the test plates to be specified. The test plates are clamped at the ends for correct load introduction at the tabs. The long sides are supported by two pairs of rails built into the loading frame with knife edge contact at the plates as shown in Fig. 2. The long edges are supported 15 mm inside the plate boundaries, with the consequence that 200 mm wide test plates had an effective width for impact loading of 170 mm.

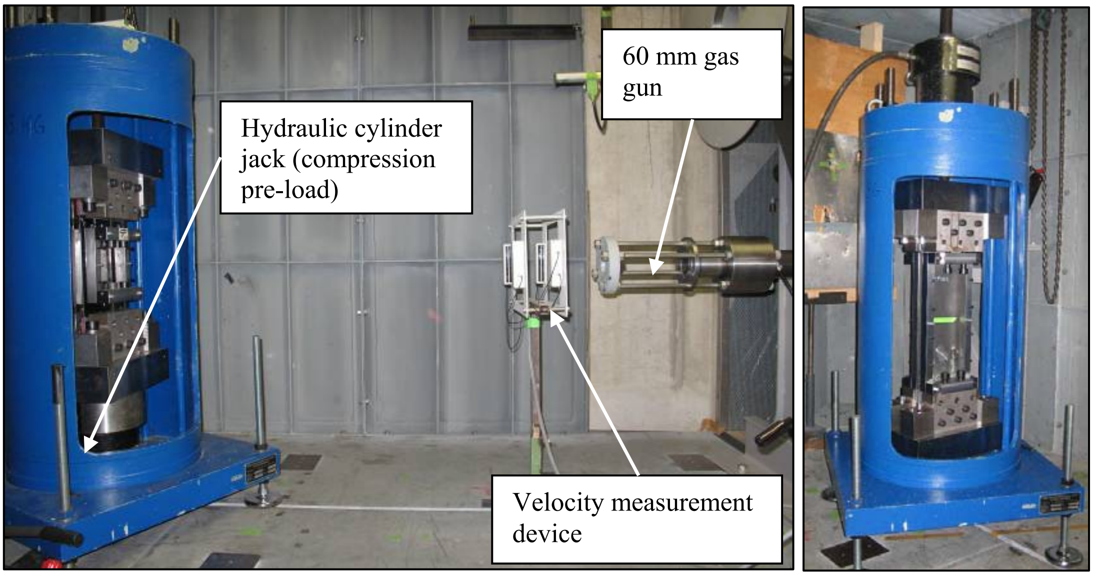


Fig. 1. Pre-stressing fixture for compression preload in the gas gun test chamber / Pre-stressing fixture for tension preload

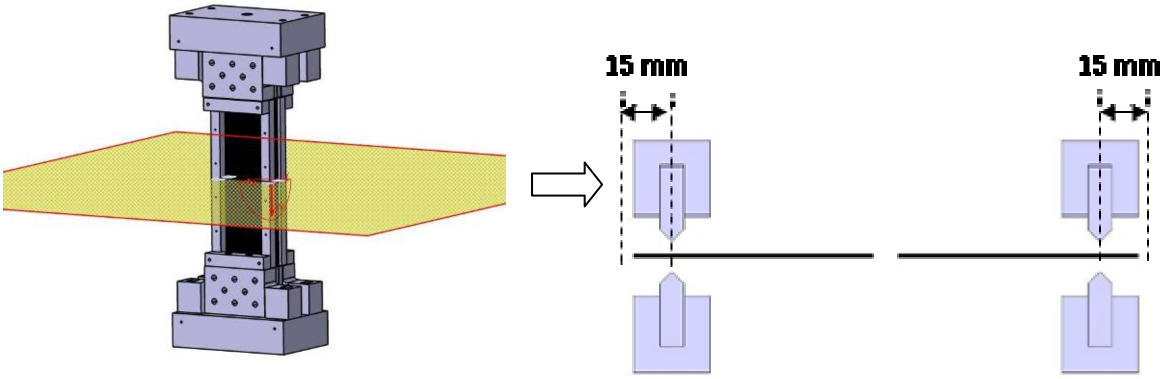


Fig. 2. Principle of lateral support through lateral rails

Tensile preloads were up to 0.25% strain, monitored by the two pairs of back-to-back strain gauges attached to the plates. For compression preloads axial strains in the plate are not suitable for controlling the preload levels since at strains below 0.25% the measured strains indicate a combined compression plus plate bending strain field due to the onset of buckling in the thin plates. The quasi-static tests on undamaged plates are used to define a compression buckling load Pb for composite plates with the same end clamping conditions and lateral rail supports. It is decided to apply compression preloads in the post-buckle range of 1.4 Pb for composite, together with preloads of 0.5 Pb in the unbuckled state.

2.2.2 Residual strength tests

The residual strength tests are conducted in a servo-hydraulic universal-axial testing machine of type Zwick 1494 (Fig. 3). When the tests are conducted under tension, the strain gauge signals are used to control that the strain distribution is uniform. In the case of a compression residual strength test on an undamaged test plate, a fifth strain gauge rosette is added in the centre of the plate to detect the initiation of buckling during loading. This method is used to establish Pb for the composite plates. All the signals of the strain gauges, the applied loads and the displacement are recorded during the quasi-static test with a frequency of 50 Hz for the data acquisition.

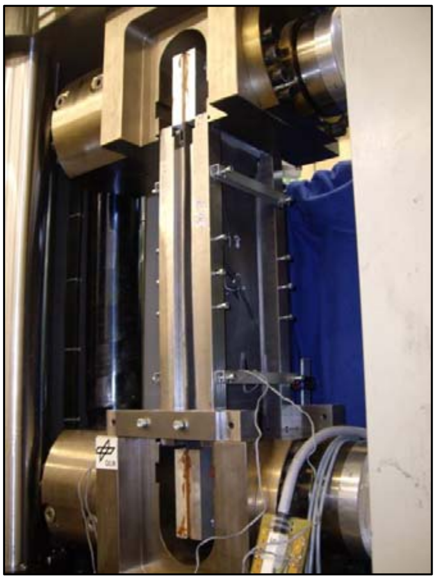


Fig. 3. Clamping and side support of the test panel in the quasi-static testing machine for a residual strength test under compression

For the residual strength tests in tension, the long side of the test plate are not supported. The 200 mm wide and 20 mm thick aluminium tabs are used to assure a uniform loading in the test plate through the 100 mm diameter loading grips in the test machine.

For the residual strength tests in compression, the long sides of the test plates are supported by two pairs of 420 mm long rails built into the Q/S testing machine with knife edge contact at the plates (Fig. 3). The boundary conditions are then the same for the high velocity impact tests and the residual strength tests.

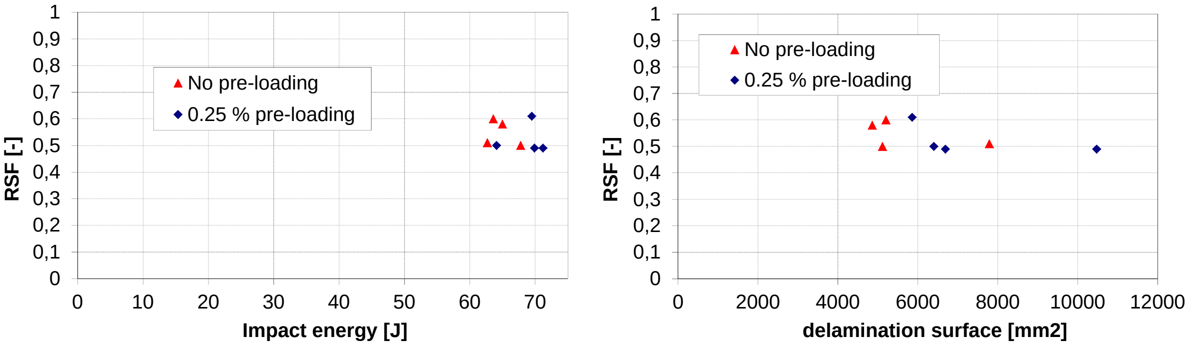
3 Test results

In order to compare the various results, a *residual strength factor (RSF)* was defined as:

RSF = failure load in damaged plate / failure load in baseline (undamaged) plate.

This factor provides a quick assessment of the effect of impact and preload on residual strengths. In the following graphs, delamination surface is determined from digital evaluation based on lock-in thermography inspection.

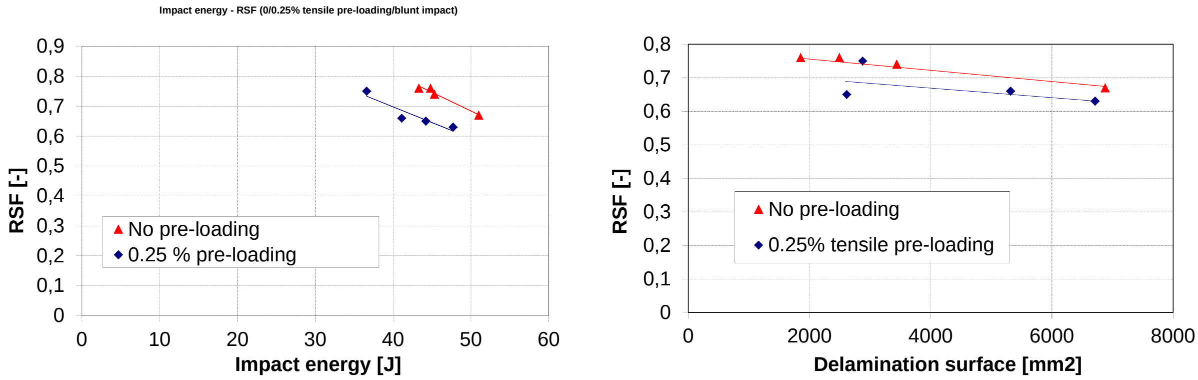
3.1 Composites with tension preload



a) **b)**

Fig. 4: Composite-tension with notch damage. Influence on RSF of:
a) impact energy and b) damage area

Fig. 4a shows the RSF for the notch tests plotted against the impact energy in the range 0.48 – 0.61, which indicates a significant reduction. It shows that provided the impact energy is high enough for penetration in these notch tests, there is no change in RSF as the energy is increased. There is a tendency for a slightly lower RSF with 0.25% tensile preloads, which does not appear to be influenced by impact energy. Fig. 4b considers the influence of impact damage, by plotting RSF against measured damage(delamination) area in mm^2 which is in the range 5000 – 10 500 mm^2. It appears that the damage area may be significantly larger for notch impact with tensile preload. However, this seems to have no influence on the measured RSF values. It is concluded that for severe notch damage, the size of the notch (which due to the 12 mm steel cube is fairly constant) determines the strength reductions, and additional delamination damage is of secondary importance.

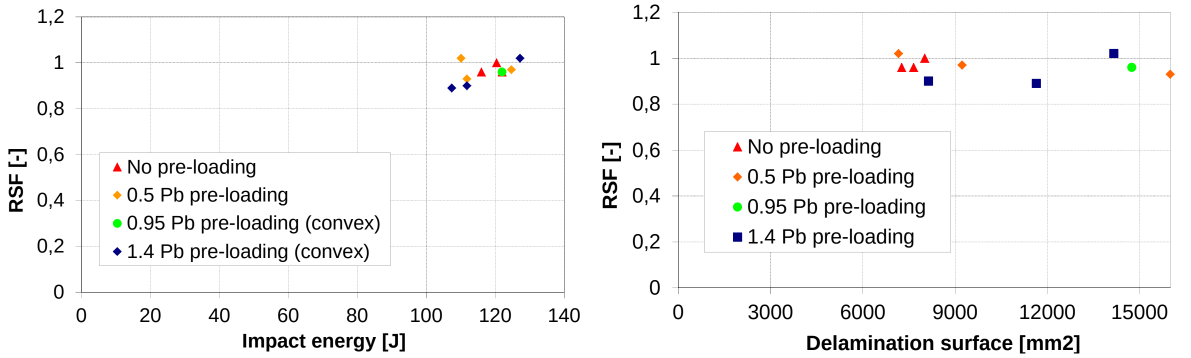


a) **b)**

Fig. 5: Composite-tension with blunt impact. Influence on RSF of:
a) impact energy and b) damage area

Fig. 5a shows a similar analysis applied to the blunt impact tests, in which RSF factors are in the range 0.63 – 0.76 indicating a less critical damage state than notch damage. Here it is seen that the differences in impact kinetic energy do have an influence on the RSF value, with higher energies causing a reduced RSF. Fig. 5b also shows some correlation between RSF and delamination area. For these blunt impacts delamination area is in the range 2000 – 7000 mm², but with reduced RSF for larger delamination areas. The graphs show that for blunt impacts there is a small but measurable reduction in RSF of about 10% due to tensile preload, which may be explained if the tensile preload causes greater delamination in blunt impact.

3.2 Composites with compression preload



a) **b)**

Fig. 6: Composite-compression with notch damage. Influence on RSF of:
a) impact energy and b) damage area

In the case of compression preloads in the pre-and post-buckled region the RSF values are in the range 0.89 – 1.02 and little influenced by notch damage. It even appears from Fig. 6a that increasing impact energy leads to higher RSF values closer to unity. The RSF values for the pre-buckled plates 0.5 Pb are very close to and sandwiched by the zero preload and buckled preload 1.4 Pb data. Fig. 6b indicates large damage areas from 7000 – 16 000 mm². Generally the preloaded plates have considerably greater damage area than the unloaded plates, but this damage in the plate does not have a strong influence on residual strengths. This may be explained if the notch and delamination damage is in the plate central impact zone, but due to the complex buckling stress field, higher stresses leading to failure are away from the centre. Fig. 7 shows the typical damage after impact (notch) in a 3.1 mm composite plate when pre-loaded at 1.4 Pb.

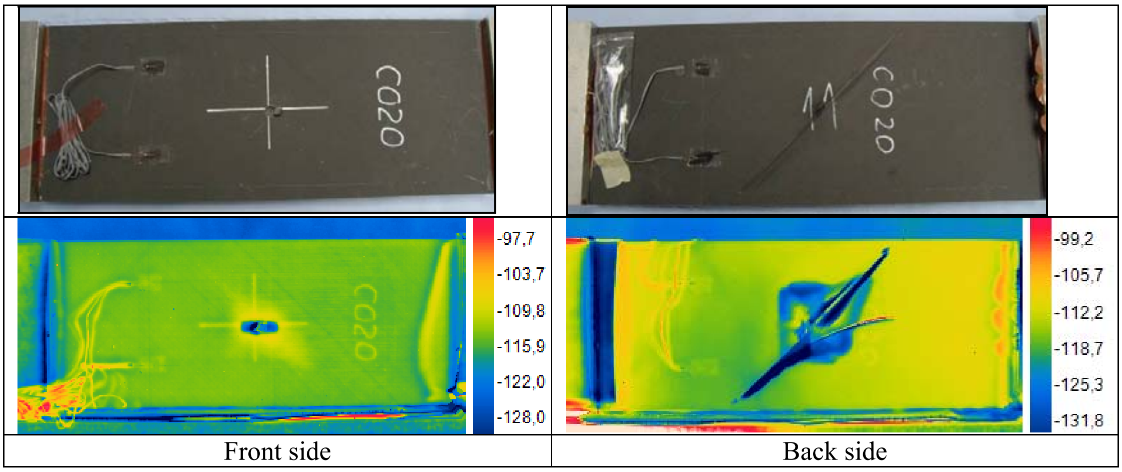


Fig. 7: Visible damage and lock-in thermography inspection after high velocity impact of a 3.1 mm composite plate, 1.4 Pb preload, notch damage, impact on convex side (V = 126.6 m/s, E = 107.4 J)

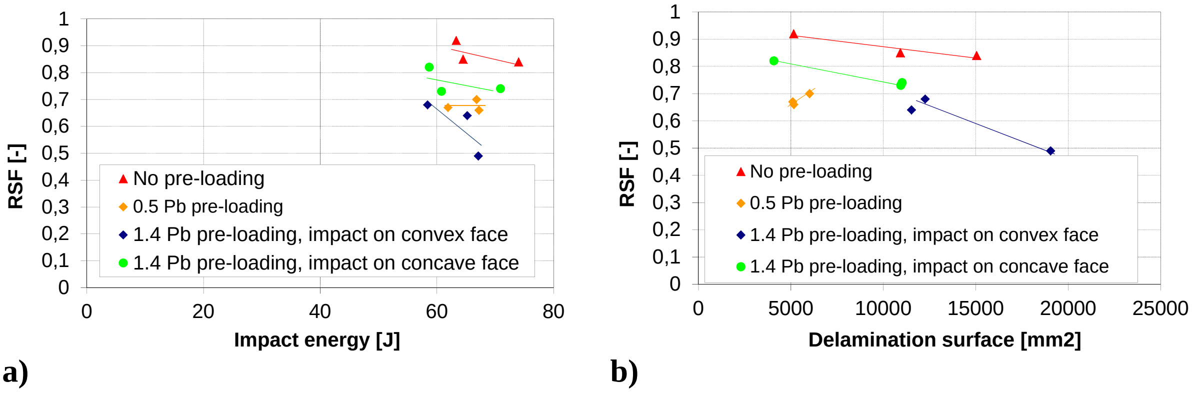
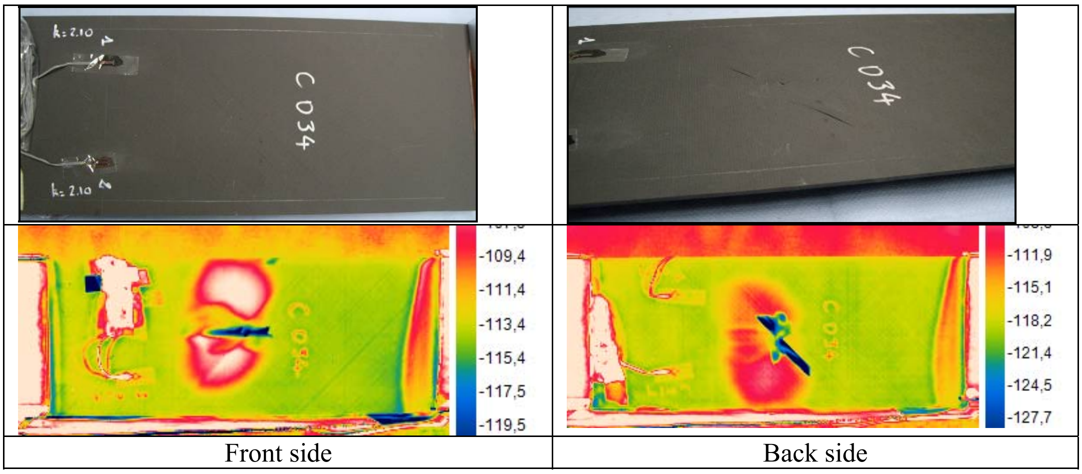


Fig. 8: Composite-compression with blunt impact. Influence on RSF of:
a) impact energy and b) damage area

In the case of blunt impact on composite plates in compression, RSF values can be significantly lower than in notch damage and have a wider range 0.49 – 0.92. Fig. 8a shows good correlation between lower RSF values and higher impact energies, particularly for convex buckling cases. There is a clear tendency of lower RSF for compression preload, with smallest reduction for 1.4 Pb preloads and concave impact, and largest for the case of convex impact. The pre-buckled plates with 0.5 Pb are sandwiched between these two extremes. The significant differences between convex and concave impacts are clearly shown in the measured damage areas in Fig. 8b. The smallest damage areas are seen in the concave impact cases from 4000 – 11 000 mm², with the largest damage areas 11 000 – 18 000 mm² in the convex impact plates. The plates without preload had 5 000 – 15 000 mm² damage and the pre-buckled plates with 0.5 Pb preload showed the smallest damage area 5 000 – 6 500 mm². Note that the visible damage in the concave impact plates after impact was considerably higher than in the convex impact plates, which thermography shows more internal delamination damage. This high damage area causes failure at lower loads and hence lower RSF values, than in the concave plates and those without preloads.

Fig. 9 shows the typical damage after blunt impact in a 3.1 mm composite plate when pre-loaded at 1.4 Pb. On the impact side, no damage is visible although the thermography shows a large delamination area.



Front side

Back side

Fig. 9: Visible damage and lock-in thermography inspection after high velocity impact of a 3.1 mm composite plate, 1.4 Pb compression preload, delamination damage, impact on convex side (V = 83.4 m/s, E = 67.1 J)

3 Conclusion

A test programme investigating the influence of pre-loads on the residual strength of composite panels after impact, representative of fuselage bay panels, has been conducted with a total of 57 composite test plates. Two pre-loading levels were considered for the compression case: 0.5 Pb (no buckling) and 1.4 Pb (with buckling) for the composite plates respectively. For preloading in the postbuckle region, two cases were investigated corresponding to an impact on the concave and convex face of the buckle. Two types of damage were of interest for the composite plates: notch damage from small hard body impactors and delamination damage from blunt impactors. Figs 7 and 9 show typical notch and delamination damage states seen from photographs and thermography images for tests in compression preload impacted on the convex face. Note that the left side figures are the impact face, with the right side figures the inside face.

The following conclusions can be drawn from the experimental results:

- For the composite plates in tension there were small reductions in residual strengths for both blunt and notch impacts. They were not very significant for the low preloads at DLL level studied here.
- For the composite plates in compression with notch damage, which were all tested and failed by buckling, there was no significant reduction in residual compression strengths despite the considerable visible damage shown in Fig. 7. At buckling failure the high failure strains were away from the central damage and holes (due to the observed buckling mode), which may explain the small influence of pre-loading on the residual strength. If the buckling mode were different, results may have been different
- The composite plates in compression with blunt impact causing delamination damage were the most critical cases studied. Delaminations as seen in Fig. 9 grew with quasi-static loads which had a strong influence on bending strengths and hence reduced buckling failure loads, although the visible damage in the plate was small.

This first study shows that compression pre-load and blunt impact may be a critical case for composite panels. Indeed, the damage is barely visible on the impact side, which makes it difficult to detect on an aircraft structure, and the residual strength of the preloaded (compression) panel decreases significantly after the impact event. This was especially seen in the presented study for a specific plate configuration (lay-up, dimensions), and specific load cases (0.5 Pb → before buckling, 1.4 Pb → after buckling).

References

[1] LIBCOS – *Significance of Load upon Impact Behaviour of Composite Structure*, EASA.2009.OP.24, European Aviation Safety Agency, Cologne, Germany, 2009

[2] Irving, P.E. et al, Effect of preload on bird strike damage in carbon fibre polymer composite beams, CAA Report, Cranfield University, CU/WA9/W30814E/62, 2004.

[3] Zhang, Z., Davies, G.A.O., Hitchings, D., Impact damage with compressive preload and post-impact compression of carbon composite plates. *Int J Impact Eng*, **22**, pp. 485-509, 1999.

[4] Heimbs, S., Heller, S., Middendorf, P., Hähnel, H., Weiße, J., Low velocity impact on CFRP plates with compressive preload: Test and modelling, *Int. J. of Impact Engineering*, **36**, pp. 1182-1193, 2009.

[5] Whittingham, B., Marshall, I.H., Mitrevski, T., Jones, R. The response of composite structures with pre-stress subject to low velocity impact damage. *Compos Struct*, **66**, pp. 685-698, 2004.

[6] Pickett, A.K. Fouinneteau, M.R.C., Middendorf, P. Test and modelling of impact on pre-loaded composite panels. *Appl. Comp. Mats*, **16**, pp. Sept. 2009, Appl. Comp. Mats, 16, 2009.

Disclaimer

This study has been carried out for the European Aviation Safety Agency by the German Aerospace Center (DLR), Institute of Structures and Design, and expresses the opinion of the organization undertaking the study.