PERFORMANCE OF COMPOSITE PLATES AFTER MULTI-SITE IMPACTS

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Abstract

Sequential multi-site low velocity impacts (LVI) were performed on CFRP composite plates with different thicknesses and the compression after impact (CAI) behaviour was then investigated. A modified CAI rig was designed and manufactured for testing thin composites. A Finite Element (FE) model of the laminate was developed using continuum shell elements. Layers of cohesive elements were inserted between sublaminates in order to model delamination initiation and growth during impacts. An energy-based damage model, developed at Imperial College and implemented into the Abaqus FE system as a user material subroutine, was employed to represent translaminar damage. Finally, the experimentally observed behaviour of the impacted specimens and the accuracy of the FE predictions are discussed.

1. Introduction

The aim of this study is to investigate the post-impact behaviour of aircraft-grade carbon/epoxy laminates containing multi-site impact damage that may arise, for example, in a hail storm. Local delaminations created by impact can grow under compression leading to global collapse of the laminate. This process can be significantly promoted by local buckling of the sublaminates separated by the delamination. Other compressive failure mechanisms include global buckling, local-global buckling and in-plane failure due to stress concentrations [1]. Review of CAI test methods indicated that use of anti-buckling plates and precise selection of dimensions of specimens are usually made to prevent global buckling and thus ensure that the test will reveal the effect of impact induced defects, e.g. delamination, on the CAI strength.

Test methods adopted by NASA and Boeing require clamping the top and bottom of the specimen and supporting the side edges to avoid global buckling. The NASA procedure prescribes a 6.35mm thickness for the specimen and the Boeing method prescribes a 4mm to 5mm thickness. The same method has been used by Prichard [2] to test thinner laminates (2mm) but the dimensions of the free portion of the panel were significantly smaller to postpone failure by global buckling. In another study by Sanchez [3], a new fixture was designed to determine CAI strength of 1.5–2.2 mm thick composite laminates. The anti-buckling part of the fixture was composed of two halves separated with a small gap in the middle of the specimen. It was designed to avoid premature failure of the thin specimen near the grips due to crushing and brooming mechanisms. Another method to delay these failure mechanisms is to use end tabs, similar to the CRAG test method [4].

This paper investigates the compression after impact performance of composite plates that have been subjected to two sequential impacts. The experimentally observed behavior is shown to be in good agreement with predictions from finite element modeling.

2. Materials

All the specimens in this study were manufactured from unidirectional prepgregs that cured in autoclave. The specimens were made of two different CFRP materials and two different lay-ups for each material. Details of the two CFRP materials and the layups are given in Table 1.

Material	**Name**	**Lay-up**	**Average thickness**
T800-M21	Thin 1	45,-45,90,0,90,0,90,-45,45	1.65mm
	Thick 1	$[45,-45,90,-45,0,45,-45,0,45,0]_s$	3.7mm
HTS-6376C	Thin 2	$[45,-45,0,90]_s$	2mm
	Thick 2	$[45,-45,0,90]_{2s.}$	4mm

Table 1 Materials and lay-ups

3. Impact testing

The impact tests were performed using a CEAST drop tower with CEAST 6.01 software controlling the test procedure and recording the test data. Each sample was placed in the pre-assembled rig in the base of the tower designed to ensure the correct location of the impact on each plate. Four bolts secured the upper and lower portion of the rig around the specimen and were tightened to 25 Nm with a torque wrench. The actual impacting was automated and involved a 2.4 kg impactor being raised to the correct height corresponding to 10J impact energy and then simply being released.

One set of impacts (referred to here are horizontally aligned impacts) were carried out on 150 mm x 100 mm specimens with the longer dimension in the direction of the 0^o layup direction. The coordinates of the impacts (expressed in xy coordinates measured in mm from the centre of the plate with x being in the zero degree direction i.e. parallel to the longer dimension of the plate) were at [-25,0] for the single impact case and [-25,0] & [15,0], or [-25,0] & [25,0] for the double-impact cases. Vertically aligned impacts were carried out on 150 mm x150mm specimens (first dimension parallel to the 0^o layup direction) at co-ordinates, in mm, [0,-25] for the single impact case and at [0,-25] & [0,15] or [0,-25] & [0,25] for the double-impact cases. Following the impacts, the large plates were trimmed to 150mmx100mm (with the longer dimension parallel to the 0^o direction). All the impact locations can be seen in Figure 1.

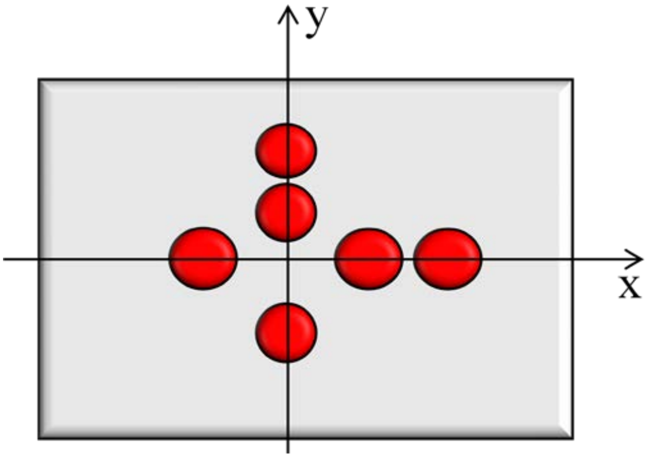


Figure 1 Impact locations

The procedure for impacts was:

- Measurement and C-scan of the specimens
- Impact of the specimens during which the force time history was recorded
- C-scan the specimens and measurement of the dent depth
- Second impact during which the force time history was recorded
- C-scan the specimens and measurement of the dent depth

On selected specimens, time-of-flight scan was taken in order to determine the location of the delaminations through thickness. Typical force-time plots and ultra sound images are shown in Figure 2.

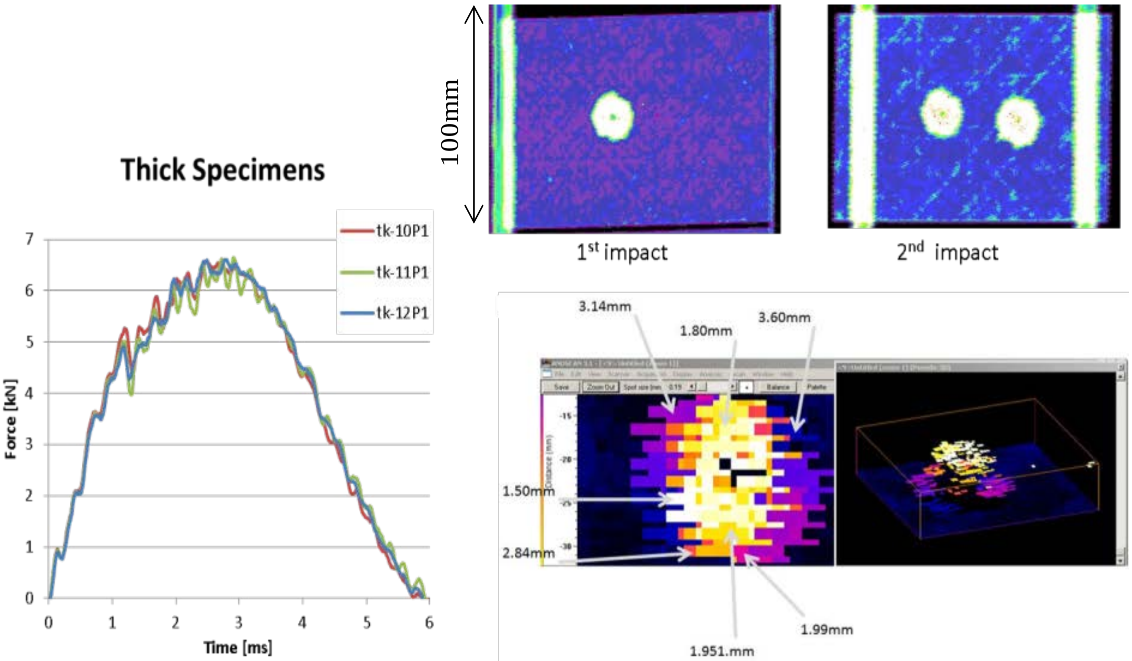
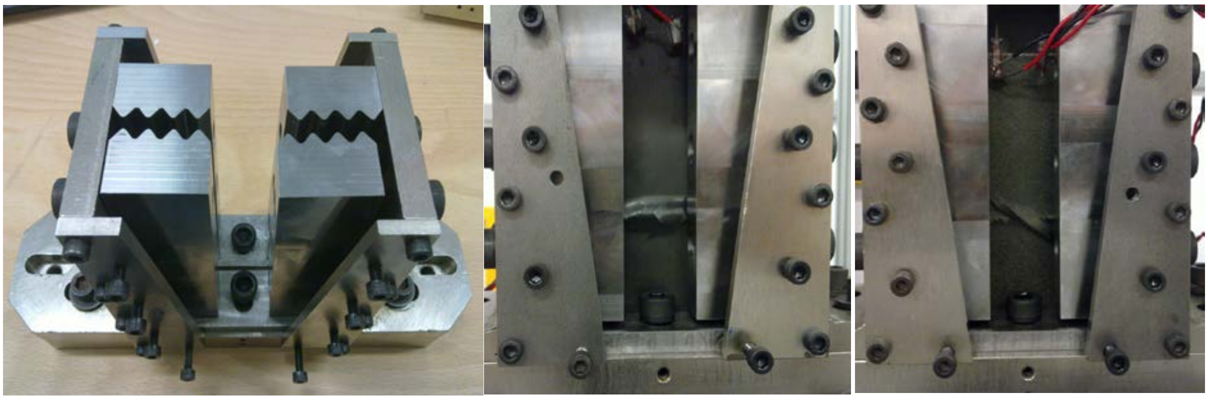


Figure 2 For thick specimens: the impact reaction forces, the c-scans and the time of flight scan

4. Compression after impact

The specimens were tested in an Instron testing machine with a 250kN load cell. In order to test in compression the thick specimens (Thick 1 and Thick 2), the standard compression fixture that is described in AITM 1-0010 [5] was used. For thin specimens, a special support fixture was designed and manufactured as shown in the left image of Figure 3 in order to avoid global buckling during compression. The clamping at the specimens edges was successfully designed so no failure occurred in the edge regions and specimens failed in a valid manner avoiding global buckling as required (Figure 3).



New fixture Impacted side Back side

Figure 3 The modified CAI fixture for thin specimens and an example of tested thin specimen

Figure 4 shows the failure loads measured in the CAI tests. For the thin specimens in the T800-M21 material there is a clear trend: the compression strength after the double horizontally aligned impacts is less than after a single impact and the larger separation distance (50 mm) between the double impacts results in a greater reduction in the CAI strength (19% less than the pristine compression strength). For thin specimens in the HTS-6376C material the CAI strength for the single impact and for the double horizontally aligned impacts with 40 mm separation are very little different to the pristine compression strength. Only the double impacts with 50 mm separation show a significant reduction in strength from the pristine case of around 14%. The residual compression strength of the thick specimens in the T800-M21 material for the double horizontally aligned impact case with a separation of 40 mm is smaller than the single impact case but with a 50mm separation the CAI of the double impact case is almost identical to the single impact. (A similar observation can be made for the vertically aligned impacts on this material.) It may be that for this material that when the two impacts are separated by more than a certain distance the CAI strength is unaffected by the second impact. However for this material the standard deviations for each test case are relatively large and so further testing is required to confirm this hypothesis. For the thick specimens in the HTS-6376C material the compression strength is virtually unaffected by single of double impacts of the energy considered here.

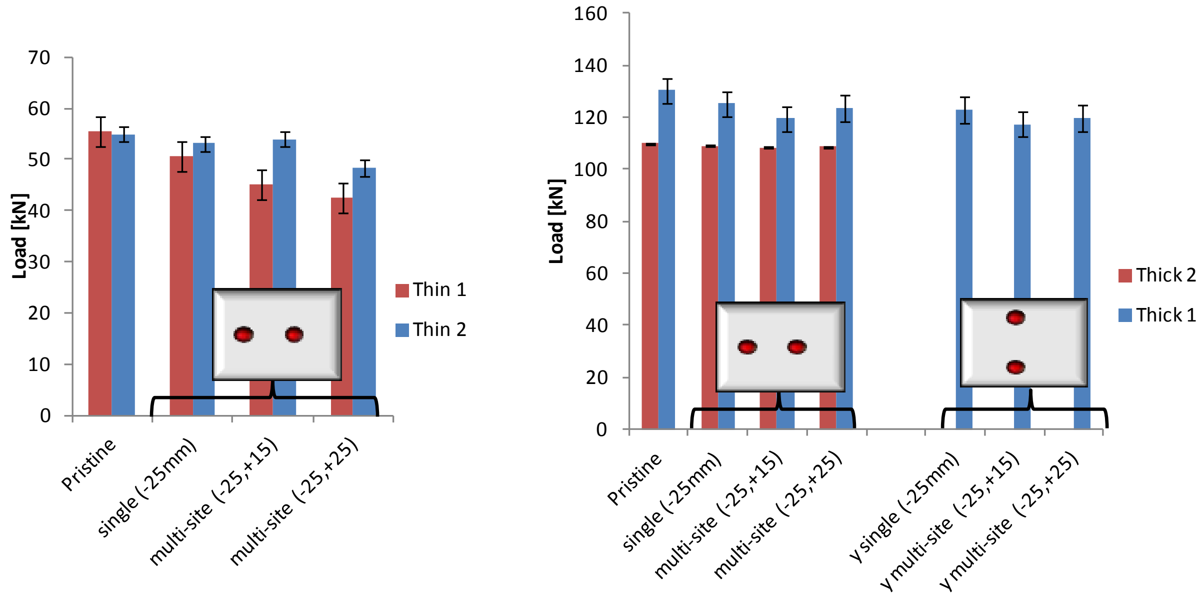


Figure 4 Experimental CAI failure loads for thin and thick specimens (see Table 1for material and lay-up)

5. FE analysis and comparison with the test results

Finite element analyses were performed using ABAQUS to model the impact and CAI behaviour. Each plate was divided into a number of sub-laminates and each of these sub-laminates was modelled with 4-node general-purpose reduced integration shell elements, S4R. Each ply was modelled with a through-thickness integration point. In order to predict damage initiation and growth within each ply, the energy-based two dimensional material model developed by Iannucci [6] was employed. This model has been implemented in ABAQUS as a VUMAT [7]. It is a continuum damage mechanics based model that can predict four failure modes; tensile fibre fracture, compressive fibre fracture, coupled in-plane shear-tensile matrix fracture (quadratic criterion) and coupled in-plane shear-compressive matrix fracture [8]. A unique feature of this model is that it has a non-linear curve for in-plane shear stress-strain. Furthermore, with this material damage model, it is possible to model irreversible strain (plastic strain) during unloading. Layers of cohesive elements were inserted between sublaminates in order to model delamination initiation and growth during impact and compression. Mesh objectivity has been also addressed within this implementation. A complete description of the material model can be found in [6] and [7].

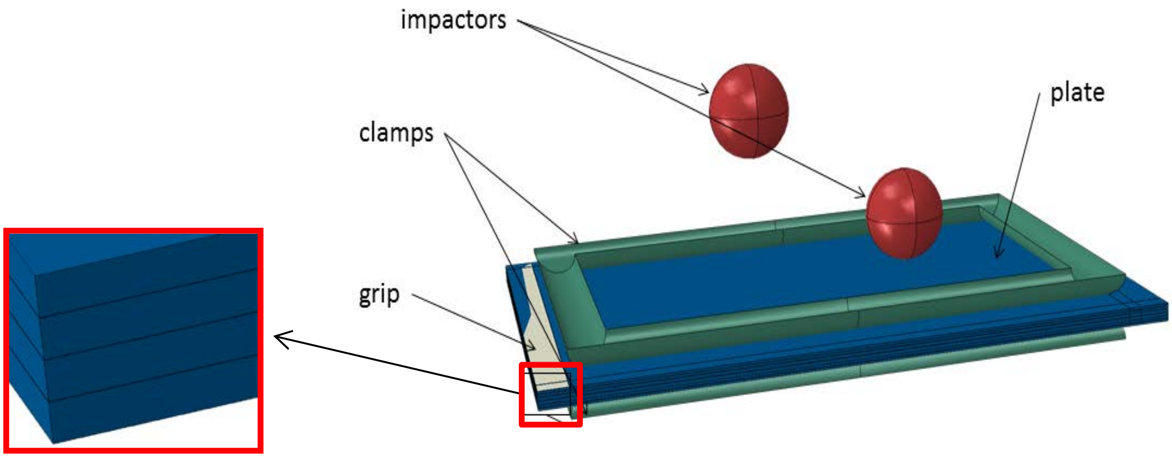
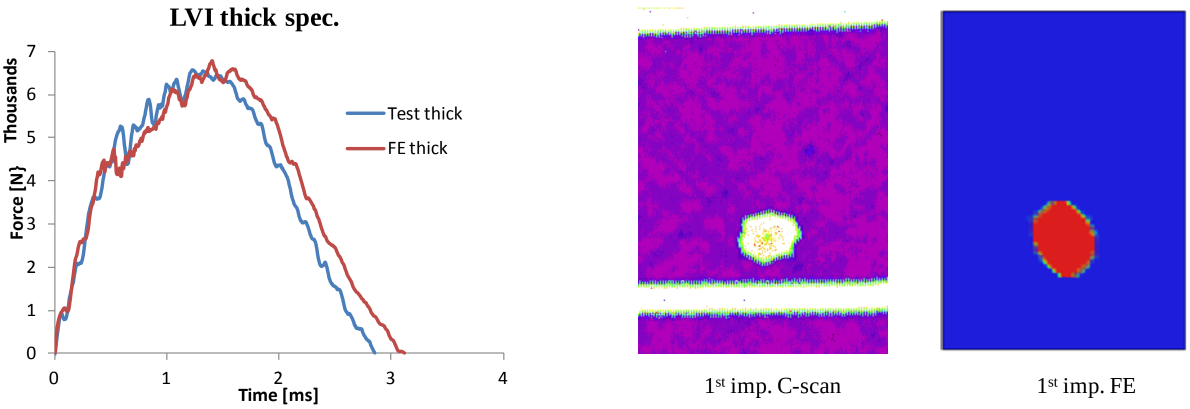


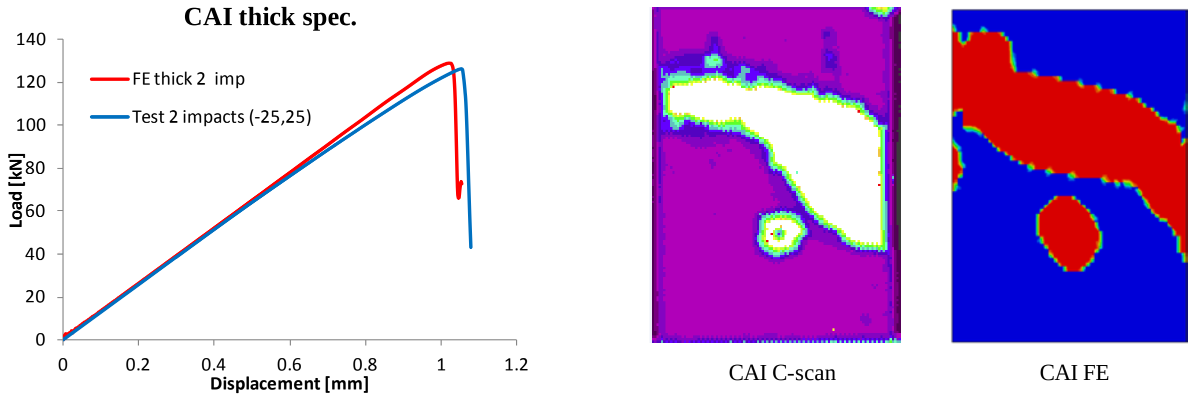
Figure 5 The impact and CAI test FE model

All impacts and CAI tests were simulated with a multi-step FE model. The steps were clamp, impact, damp, clamp, impact, damp and finally compression, Typical experimentally observed and FE-predicted impact force-time plots and CAI load-displacement plots together with c-scans and FE delamination predictions are shown inFigure 6. As can be seen in, the model provides good agreement with the force development during the impact and CAI tests and a reasonable prediction of delamination damage, although it slightly over predicts the impact case damage area.



1st imp. C-scan

1st imp. FE



CAI C-scan

CAI FE

Figure 6 LVI and CAI comparisson for thick specimen

6. Conclusions

In this study the compressive performance of carbon composite laminates subjected to single and double impacts has been investigated both experimentally and with FE analyses. To measure the compression response of impacted thin laminates a special CAI fixture was designed and manufactured. The support arrangement at the specimen edges was successfully designed so that no failure occurred in the edge regions and the specimen failed in a valid manner, avoiding global buckling as required. The influence of multi-site impacts on the residual compression strength was investigated and concluded that the strength is dependent on skin thickness and the separation of the impacts. Finally FE model predictions were shown to achieve a good agreement with the force recorded during the impact and CAI tests and the experimentally observed damage area.

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