DYNAMIC LOADING OF FIBRE-REINFORCED LAMINATES: EXPERIMENTS AND SIMULATIONS

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Abstract.
Fibre-reinforced polymers (FRPs) used in aerospace and sports products can be exposed to different in-service conditions such as tensile and dynamic bending deformations caused by impact loading. Composite materials subjected to such loads demonstrate various damage modes such as matrix cracking, delamination and, ultimately, ply fracture. This study deals with analysis of damage in two types of carbon fibre-reinforced polymers - cross-ply and woven laminates - under impact loading. The first type of FRP is exposed to conditions of impact fatigue (IF). Another type of laminate – reinforced with 2/2 twill fabric – was loaded in single impacts. The properties of, and damage evolution in, the studied two types of laminates were analysed using a combination of mechanical testing and microstructural and damage studies using optical microscopy and X-ray micro computed tomography. Dynamic tests on cross-ply laminates were implemented using uni-axial tensile impact loading. Advanced FE models were developed in Abaqus/Explicit to characterise the response of FRP laminates to impact loading conditions in order to elucidate their dynamical mechanical behaviour. Transient 3D finite-element models for uni-axial tensile and Izod-type bending impact loading regimes for tested samples of FRP cross-ply laminates were developed based on direct introduction of hammer-specimen interaction.

1. Introduction

Fibre-reinforced polymers (FRPs) are broadly used in aerospace and naval structures as well as in automotive and sports products due to their high specific stiffness and strength, and ease to manufacture shapes tailored for applications. Woven-fabric composite laminates offer good resistance to fracture and transverse rupture and high impact strength compared to their unidirectional and cross-ply tape counterparts [1]. These properties have attracted the sports industry to incorporate woven CFRP laminates in the design of sports products that could be subjected to large-deflection bending and multiple impacts in service conditions. This type of dynamic loads generate high local stresses/strains leading to complex damage modes due to heterogeneity and anisotropy of composite laminates. The damage mechanisms caused by out-of-plane impact loads in laminates are matrix cracking, fibre breakage and delamination at interfaces within the composite structure [2]. Impact damage and, in particular, delamination occurring at low-velocity impact cause a significant decrease in the material's in-plane compressive strength and stiffness. Apart from the impact study of woven CFRP laminates, impact-fatigue behaviour of cross-ply CFRP laminates is also investigated here. A reason for multiple low-energy impacts (known as impact fatigue (IF)) in laminates could be, for instance, wind gusts during a flight. IF can be defined as a repetition of low-energy impacts with energy amplitudes insufficient to cause a total failure of a component in a single impact [3]. The detrimental effects of IF on the structural integrity of components can be observed after relatively few impacts, even at force amplitudes significantly lower than the durability limit in a standard fatigue regime [4]. Up to now IF was not accounted in design of composite structures for service life. The method that has been used for years to predict the service life is standard- fatigue (SF) analysis, e.g. the rainflow algorithm in combination with the Miner's rule. However, sharp stress peaks in IF observed in the stress spectrum are treated as SF data, which could result in wrong estimation of fatigue life.

The low-velocity impact response of woven-fabric composite laminates has been extensively treated in the literature employing experimental studies, analytical formulations and numerical implementations [5-8]. However, majority of the studies are dedicated to the impact behaviour of composites tested with drop-weight tests, which usually caused localised damage such as penetration and perforation. A large-deflection dynamic bending behaviour of laminate composites caused by a pendulum-type impactor is rarely investigated. In this connection, the authors studied earlier large-deflection behaviour of woven laminates under quasi-static bending and tensile loads [9-11]. Investigation of impact-fatigue behaviour of CFRP composites has received little attention to date. In this regard few studies can be found (e.g. Silberschmidt *et al*. [12] and Casas-Rodriguez *et al*. [3, 4]), where an instrumented impactor was used to study damage in adhesively bonded CFRP joints under repeated impacts; the loading mode there was tensile.

In the present work, a large-deflection bending behaviour of woven-fabric CFRP laminates subjected to impact loads is studied. Flexural impact tests were carried out using a pendulum-type impact tester, and damage was investigated with optical microscopy. A multi-body-dynamics impact finite-element model was developed in Abaqus/Explicit and the obtained modelling results have good agreement with our experimental data. Additionally, impact-fatigue behaviour of cross-ply laminates is studied under uni-axial tensile dynamic loading conditions, employing a unique testing system at Loughborough University, capable of subjecting specimens to uni-axial tensile dynamic loading. In those experiments, CFRP cross-ply specimens with a central hole were subjected to multiple impacts, and the damage initiation and propagation around the hole were examined. Effects of damage on the fatigue life were assessed with X-ray micro-CT and the use of a load-time model. Numerical models developed in Abaqus/Explicit, which utilised cohesive-zone elements (CZEs), served the purpose of validating the experimental results.

2. Experimental methods

2.1. Specimen Preparation

Two types of woven and cross-ply CFRP laminates were tested to obtain their material parameters. Woven specimens were prepared from laminates of woven fabric made of carbon fibres reinforcing a thermoplastic polyurethane (TPU) polymer matrix. The fabric was produced from 0°/90° prepregs in the form of four plies designated as $[0°,90°]_{2s}$, where 0° and 90° represent yarns in the warp and weft directions, respectively. The woven laminate had a 2/2 twill weaving pattern with a fibre volume fraction of 45%; the fabric had the same number of yarns in the warp and weft directions. Un-notched rectangular specimens of 40 mm length, 25 mm width and 1.0 mm thickness (each laminate had four layers of 0.25 mm thickness) were prepared. Cross-ply CFRP samples were made using a uni-directional carbon/epoxy T700/LTM45 prepreg with a nominal ply thickness of 0.128 mm. Mechanical properties of the cross-ply laminates, measured at Loughborough University, are displayed in Table 1. Two cross-ply lay-ups of $0_2/90_4/0_2$ and $0_4/90_8/0_4$ (we use here different notation for lay-ups to differentiate between the composite types) were selected, as that enabled a number of failure mechanisms and the effect of doubling the thickness on the fatigue life to be investigated in a relatively simple system. Similarly, elastic material parameters determined from tests in the warp, weft and shear directions for woven CFRP specimens are also presented in Table 1.

Property	E_{11} (GPa)	E_{22} (GPa)	E_{33} (GPa)	$G_{12}=G_{23}$ (GPa)	G_{13} (GPa)	$\nu_{12}=\nu_{23}$	ν_{13}
Cross-ply	127.0	9.1	9.1	5.6	4.0	0.31	0.4
Woven	44.7	44.7	8.0	4.4	3.0	0.05	0.3

Table 1. Properties of cross-ply and woven CFRP composites at room temperature

2.2. Experimental procedure

2.2.1 Impact tests of woven CFRP laminates

Dynamic impact tests were carried out on an instrumented pendulum-type CEAST Resil impactor according to ISO 180 standard. In the impact tests of woven CFRP, the bottom of the specimen was fixed firmly in the machine vice. The upper 30 mm of the specimen was struck by the striking nose of the pendulum hammer with a controlled level of energy, resulting in dynamic large-deflection bending. In this work, a calibrated impact hammer with a mass of 0.6746 kg and length of 0.3268 m was used; which can generate an impact of maximum energy of 2 J at impact velocity of 3.46 m/s corresponding to the initial angle of

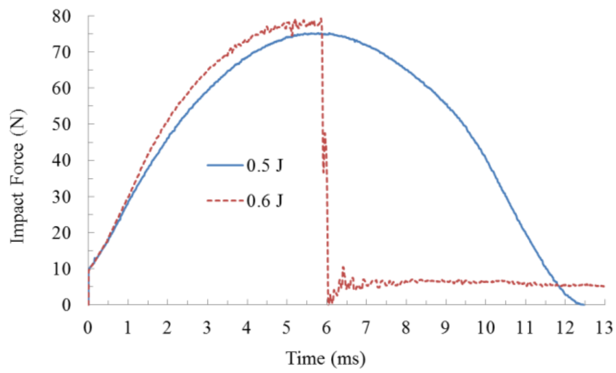

Figure 1. Force-time response of twill 2/2 woven CFRP laminate in impact tests with different energy levels

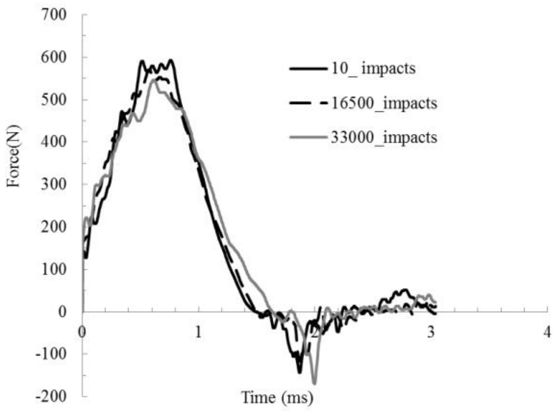

Figure 2. Force *vs*. time response in various cycles of impact-fatigue life

150° to the striking position. Woven CFRP specimens were tested at various energy levels to determine the energy inducing the ultimate fracture of the specimen. It was found that the specimen fractured at 0.6 J .The rest of the tests were carried at 0.5 J to study the behaviour of sub-critical damage modes such as matrix cracking and delamination. Typical records of force *vs*. time for un-fractured and fractured CFRP specimens are presented in Figure 1. At 0.5 J, the loading and unloading portions of the curve have a nearly symmetric parabolic shape suggesting that the respective stages during the contact duration are almost the same and no significant damage has occurred. The maximum impact force at 0.6 J energy, causing the specimen's ultimate fracture, is higher. Here, a higher impact energy induces larger deformation and therefore, larger impact force. The respective load-time graph in Figure 1 shows oscillations due to significant damage inside the specimen before its ultimate bending fracture. The ultimate fabric fracture is represented by the sudden drop in contact force implying a momentary loss of contact between the impactor and specimen.

2.2.2 Impact-fatigue tests of cross-ply CFRP laminates

Cross-ply CFRP specimens were tested to analyse fatigue crack growth under repeated uniaxial tensile impacts. The specimen's configuration, as shown in Figure 3, was adopted in conformity with ISO 8256, with modification to fit the tensile impact machine. Those specimens were impacted 33000 times to the state where intra-ply damage occurred, and force *vs*. time data were recorded as shown in Figure 2. The force-time responses were selected at the initial life of the specimen (10 impacts), its half-life (16500 impacts), and 33000 impacts (total life). From Figure 2 it can be seen that the maximum force response remains constant, while the time required for the force to vanish is increasing continuously. This trend will be analysed in terms of damage formation in the specimen; hence, X- ray micro-CT analysis was undertaken.

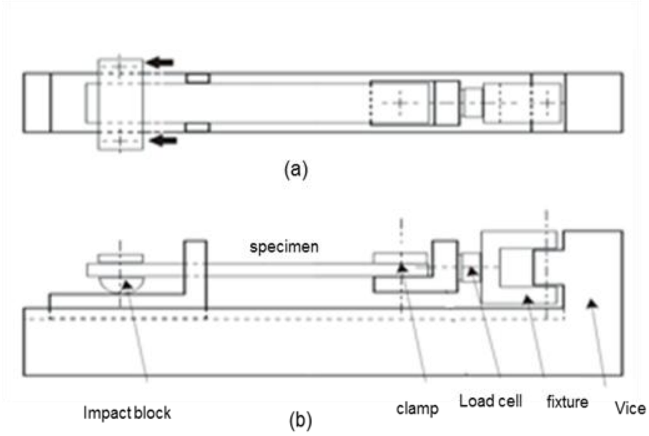

Figure 3. Schematic of specimen fixture for impact fatigue. (a) Top view, arrows denote impact loading direction, (b) Side view

2.3 Microscopic analysis of woven CFRP

In this work, an OLYMPUS BX-60M microscope was used to capture the images of the through-thickness side edge of the un-fractured specimen to observe the barely visible damage on the specimen surface. Interlaminar damage developed in the large-deflection dynamic bending is presented in Figure 4. The main mode of damage is delamination along the specimen's longitudinal axis that was expected due to high in-plane shear stresses. At this stage of loading, weft-yarn cracking (intra-ply delamination) can also be observed in the micrograph shown in Figure 4b. Here, it can be observed that damage initiation occurred at the weft-yarn edge (crimp location) and then propagated into the weft yarn. Some of these damage modes, e. g. delamination, are incorporated in our FE models.

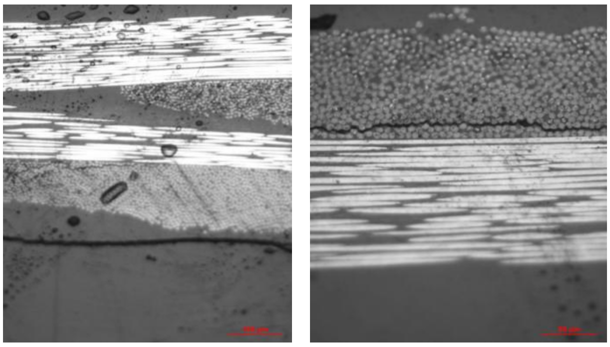

Figure 4 (a) Inter-ply delamination in CFRP laminate, (b**)** Intra-ply delamination in weft tow in CFRP laminate

2.4 X-ray micro computed tomography analysis of IF specimens

Sscenarios of inter-ply and intra-ply damage initiation and progression were assessed with X-ray micro computed tomography (mCT) for a single sample after specific stages in its IF life to describe the realisation of damage scenarios for various numbers of impacts. During testing it was observed that:

- initiation of axial splits occurred at 4000 impacts;
- inner delaminations at the hole edge appeared at 15000 impacts;

- free-edge delaminations initiated at 18000 impacts;
- free-edge delaminations propagated along the length of the specimen at 30000 impacts;
- intra-ply cracks localised in the gauge section at 32700-33000 impacts.

From Figures 5 and 6, which present the state of the specimens at the last stages of damage, it can be suggested that the increase in the time response with IF history could be related with the initiation of free-edge delaminations, appearing after a half-life of the specimen.

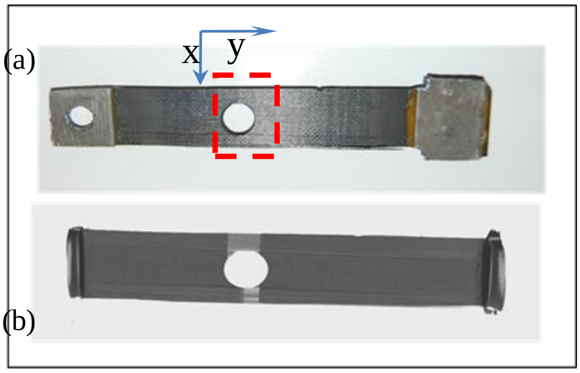

Figure 5. (a) Macroscopic evaluation with (arrows denote slicing directions); (b) semi-transparent X-ray front view of whole specimen at final stage of damage

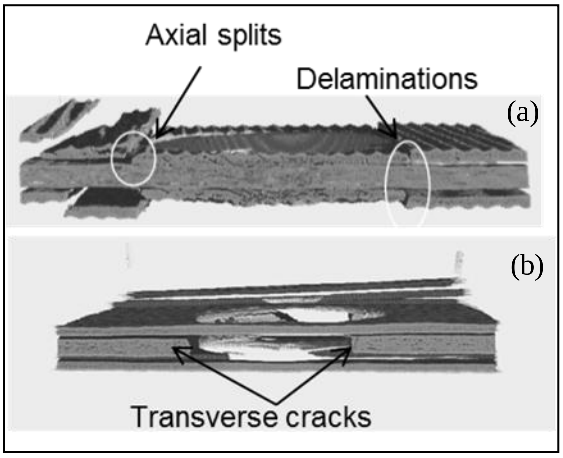

Figure 6. X slices (a) and Y slices (b) at final stages of damage

3. Finite-element modelling

3.1. Modelling impact of woven laminates

Finite-element models were developed in the commercial FE package ABAQUS/ Explicit to investigate large-deflection dynamic bending of tested composite laminates and the resulting inter-ply damage. Two FE models – Models A and B – were developed representing the impact tests on, respectively, un-fractured and fractured CFRP laminates. The modelled geometry of Model A is shown in Figure 7 along with mesh and boundary conditions.

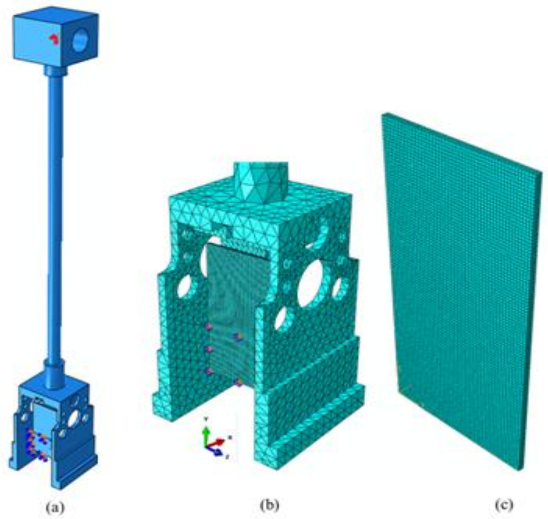

Figure 7. Impact test model (a); hammer-specimen contact interaction (b); mesh of specimen (c)

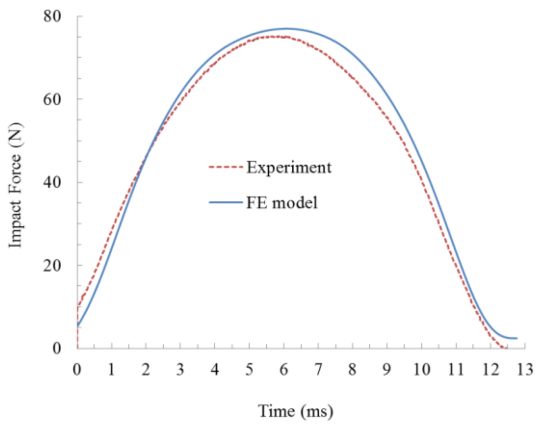

Figure 8. Comparison of experimental and numerical results in terms of force-time response of CFRP woven laminates at 0.5 J impact energy

This model was developed first to validate the dynamic contact behaviour of the hammer and specimen without incorporating any damage into simulations. The hammer was discretised with 4-noded linear tetrahedron C3D4 elements, whereas the specimen was meshed with 8-noded linear brick C3D8R elements using a structured meshing technique. In Model B representing the impact test for impact energy of 0.6 J, cohesive-zone elements COH3D8 were introduced at the interface between the laminate's plies based on delamination observed in the microscopy of the specimen. Elastic properties of woven CFRP in Table 1 were assigned to the plies and damage properties of interlaminar cohesive layers were taken from the previous work of the authors [9]. Initial angular velocities of 5.33 rad/s and 5.81 rad/s were applied to the whole hammer, corresponding to the impact energies of 0.5 J and 0.6 J, in Models A and B, respectively. Intralaminar damage in Model B for impact energy of 0.6 J was modeled using cohesive-zone elements (CZEs). CZEs have the ability to capture the onset and propagation of delamination [9, 13, 14]. Interlaminar damage modes in composite laminates initiate and propagate under the combined influence of normal and shear stresses. The nominal quadratic stress criterion was used for damage initiation; damage propagation was based on the criterion proposed by Benzeggah and Kenane [15].

3.1.1. Discussion of results

Results of experimental tests and numerical simulations for the large-deflection dynamic bending behaviour of woven CFRP laminates are presented in this section. The load-time response calculated with our numerical Model A of woven CFRP is compared with the respective experimental curve of un-fractured specimen in Figure 9. The load peak in the FE model is slightly higher than the experimental one. This discrepancy may be due to the fact that the FE model did not take into account real-life energy losses due to material viscous damping and friction between the interacting parts of the experimental setup. However, the contact duration is almost the same, implying that the stiffness of the impacted specimen was accurately modelled.The force-time response of FE Model B, which incorporated only

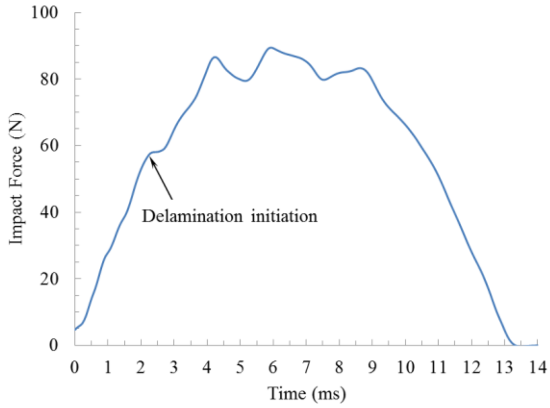

Figure 9. Force *vs*. time response of FE Model B of woven CFRP laminate incorporating delamination damage at 0.6 J impact energy

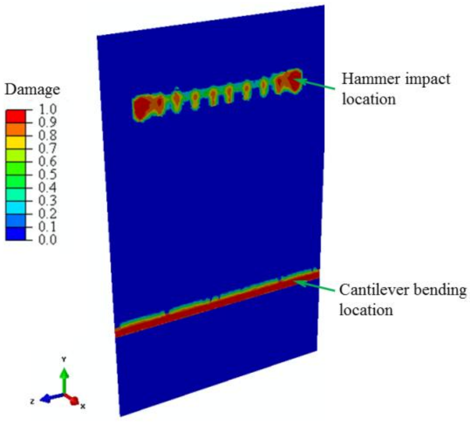

Figure 10. Interlaminar delamination damage in Model B of woven CFRP laminate at 0.6 J impact energy

delamination damage, is presented in Figure 10. Delamination initiation is represented by a first load drop at about 2 ms; delamination progresses as the load increases. Maximum damage can be seen in Figure 9 at about 6.5 ms where the impact force reaches its peak. In this simulation, delamination initiated first at the point of hammer impact and then at the bending location of the cantilevered CFRP specimen.

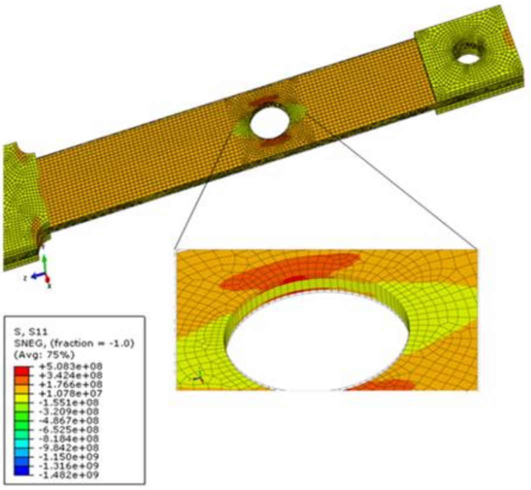

Figure 11. Principal stress contour in loading direction that indicate damage initiation in top and bottom 0º plies as well as delamination initiation at 0/90 and 90/0 interfaces

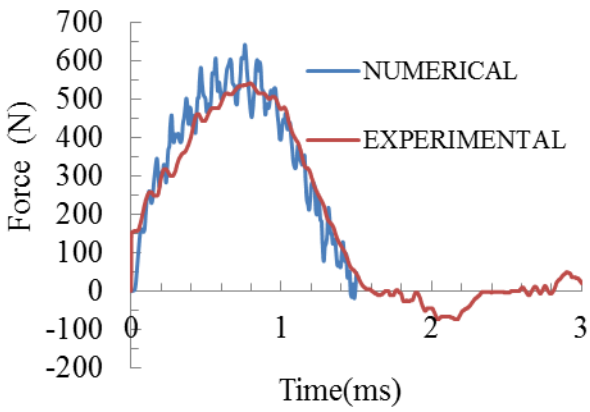

Figure 12. Comparison of impact force history for experimental data and numerical analyses

3.2. Cross-ply CFRP laminates: Modelling and results

Single-impact results revealed successful modelling of cross-ply CFRP composite laminates identifying areas of stress concentration as seen in Figure 11. Furthermore, the calculated force- time response is in good agreement with the experiment as shown in Figure 12. This is the first step in development of simulation procedures for modelling multiple impacts with the use of CZE. An important problem here is a selection of the CZE properties; a quasi-static model was built for that reason. The obtained results revealed that the stiffness was matching that in our experiments, and realisation of damage progression scenarios was satisfying. In Figure 13, a model of one-quarter symmetric portion of the central-hole section is shown.

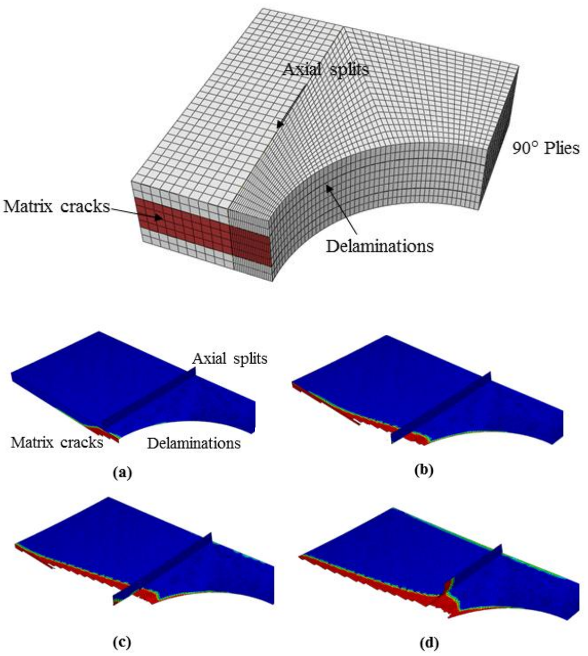

Figure 13. (top) One-quarter model of central section of specimen. Individual partitions for insertion of CZE are shown for each different damage mode
(bottom) Isolated CZE sections highlighting damage progression in notched area

CZEs were placed in areas where matrix cracks, axial splits and delaminations were observed experimentally. The main stages of damage progression scenarios are as follows:

1. Isolated damage at the hole edge due to matrix cracking in the 90° plies. It was accompanied by inner delamination at the interfaces at 45°/-45° from the hole centre propagating towards the middle of the hole in a clockwise manner Figure 13b.
2. Almost simultaneous generation of 0° splits occurred that increased in length in either way with increasing number of impacts but was always adjacent to the hole as seen in Figure 13c.
3. Damage propagated across the width of the specimen in the form of delamination (Figure 13d). As loading continued, delamination at the hole and specimen's free edge propagated towards each other. When they became close, delamination though the entire specimen's width occurred. Final catastrophic failure occurred when intra-ply matrix cracks

propagated fully through the thickness and width of the gauge section, resulting in a complete removal of the 90° ply at the gauge area.

4. Conclusions

The dynamic behaviour of woven CFRP laminates under large-deflection bending was studied using experimental tests and numerical simulations, while cross-ply laminates were investigated for conditions of impact fatigue. Both types of test demonstrated complex scenarios of spatio-temporal evolution of damage modes. Those modes were studied by means of microscopic analysis (optical and mCT). Identification of damaged areas was used for introduction of CZE into FE models. The models helped to gain a better understanding of multi-body impact dynamics in dynamic loading of composite specimens. The obtained FE results validated the experiments. The next step will be dealing with dynamic bending of woven-fabric reinforced laminates and multiple damage modes and accounting for cumulative result of multiple impacts in the case of cross-ply laminates.

6. References

[1] Ernst G, Vogler M, Hühne C, Rolfes R. Multiscale progressive failure analysis of textile composites. *Composites Science and Technology*, **70**(1):61-72 (2010).
[2] Menna C, Asprone D, Caprino G, Lopresto V, Prota A. Numerical simulation of impact tests on GFRP composite laminates. *International Journal of Impact Engineering*, **38**(8–9):677-85 (2011).
[3] Casas-Rodriguez J, Ashcroft IA, Silberschmidt VV. Damage in adhesively bonded CFRP joints: Sinusoidal and impact-fatigue. *Composites Science and Technology*, **68**(13):2663-70 (2008).
[4] Casas-Rodriguez J, Ashcroft IA, Silberschmidt VV. Delamination in adhesively bonded CFRP joints: Standard fatigue, impact-fatigue and intermittent impact. *Composites Science and Technology*, **68**(12):2401-9 (2008).
[5] Abrate S. Modeling of impacts on composite structures. *Composite Structures*, **51**(2):129-38 (2001).
[6] Iannucci L, Willows M. An energy based damage mechanics approach to modelling impact onto woven composite materials--Part I: Numerical models. *Composites Part A: Applied Science and Manufacturing*, **37**(11):2041-56 (2006).
[7] Naik N, Chandra Sekher Y, Meduri S. Damage in woven-fabric composites subjected to low-velocity impact. *Composites Science and Technology*, **60**(5):731-44 (2000).
[8] Reyes G, Sharma U. Modeling and damage repair of woven thermoplastic composites subjected to low velocity impact. *Composite Structures*, **92**(2):523-31 (2010).
[9] Ullah H, Harland AR, Lucas T, Price D, Silberschmidt VV. Finite-element modelling of bending of CFRP laminates: Multiple delaminations. *Computational Materials Science*, **52**(1):147-56 (2012).
[10] Ullah H, Harland AR, Lucas T, Price D, Silberschmidt VV. Analysis of nonlinear deformations and damage in CFRP textile laminates. *Journal of Physics: Conference Series*, **305**:12045 (2011).
[11] Ullah H, Harland AR, Blenkinsopp R, Lucas T, Price D, Silberschmidt VV. Analysis of nonlinear shear deformations in CFRP and GFRP textile laminates. *Applied Mechanics and Materials*, **70**:363-8 (2011).
[12] Silberschmidt VV, Casas-Rodriguez JP, Ashcroft IA. Impact Fatigue of Adhesive Joints. *Key Engineering Materials*, **399**:71-8 (2009).
[13] Turon A, Davila CG, Camanho PP, Costa J. An engineering solution for mesh size effects in the simulation of delamination using cohesive zone models. *Engineering Fracture Mechanics*, **74**(10):1665-82 (2007).
[14] Ullah H, Harland AR, Silberschmidt VV. Experimental and numerical analysis of damage in woven GFRP composites under large-deflection bending. *Applied Composite Materials*, DOI: 10.1007/s10443-011-9242-7 (2011).
[15] Benzeggagh ML, Kenane M. Measurement of mixed-mode delamination fracture toughness of unidirectional glass/epoxy composites with mixed-mode bending apparatus. *Composites Science and Technology*, **56**(4):439-49 (1996).