High-fidelity damage modelling of CFRP laminates for impact and crashworthiness applications – dynamic tube crushing simulations

D. E. Sommer[1*]*, D.* Thomson[1*]*, O.* Falcó[1*] *G.* Quino[1], *H.* Cui[2] and *N.* Petrinic[1]

[1] Department of Engineering Science, University of Oxford, Oxford, United Kingdom.
[2] School of Civil Aviation, Northwestern Polytechnical University, Suzhou, China.

Abstract. Drop weight impact experiments were conducted on angle-ply carbon fibre reinforced polymer (CFRP) composite crush tubes. The dynamic response was modelled using explicit finite element methods and continuum damage mechanics and cohesive zone modelling in both Abaqus/Explicit and LS-DYNA. User-defined constitutive models for the intra-ply behaviour were used and a fibre-aligned meshing technique was implemented. The results of the experiments and simulations are compared to evaluate accuracy of the different modelling techniques, highlighting the advantages and drawbacks of each approach. Among these, the choice of meshing strategy is shown to be especially important in capturing the physical propagation of cracks and damage mechanisms in CFRP laminates.

1 Introduction

For the finite element analysis of composite laminates under high energy dynamic loading, where significant damage may be expected, an accurate prediction of the damage modes such as transverse matrix cracks, axial splits (fibre/matrix shearing), fibre kinking, crushing and delamination can be just as important as the prediction of the dissipated energy. In terms of energy absorbtion, CFRP are presented as a good candidate owing to their enhanced capability with high specific strength, stiffness and fracture toughness. However, the competition between the different energy-dissipating damage modes on composite, present a difficult challenge for accurate predictions of both strength and failure mechanisms.

In the particular case of crashworthiness and crushing problems on tubular structures, more complex scenarios need to be assessed related to geometries and material modelling discretization [1]. The use of unaligned meshes, even when paired with advanced 3D damage models, has shown limited ability to describe the propagation of matrix cracks through the material, which can severely affect the accuracy of the model beyond the initial onset of damage. Previous numerical modelling work on the crushing of CFRP tubes has shown that even coarse, unaligned meshes can produce reasonable results in terms of the overall force-

* Corresponding author: drew.sommer@eng.ox.ac.uk (DES); daniel.thomson@eng.ox.ac.uk (DT); olben.falcosalcines@eng.ox.ac.uk (OFS)

displacement and energy dissipation rate, when used with adequately calibrated material and interface parameters [2-4]. However, these models may lack the ability to describe the physical matrix cracking and inter-ply delamination mechanisms. This, and the use of fitted material parameters, may limit the predictive capability of these models outside of the test cases for which the material parameters have been calibrated. Instead, a modelling approach based on aligned-mesh structuring and crack-band erosion are much better suited to capture the crack paths and complex interactions between interlaminar and intralaminar damage modes [5], which may produce more physically accurate results, based entirely on experimentally measured material parameters without the use of curve-fitting.

In the present work, a series of drop-tower tests on cylindrical CFRP tubes have been modelled using different meshing techniques and damage evolution models. The crush tubes were impacted along the axial direction, causing extensive matrix cracking and delamination damage along their length until the impact energy was completely dissipated. Due to the types and the extent of damage produced these test cases can prove challenging to model, making them well suited for benchmarking purposes. In this work, the above test case has been used to investigate the suitability of different modelling techniques for dynamic loading, using different constitutive models [6, 7] and different finite element meshing strategies: (i) a traditional meshing technique was used, which consisted of regular structured brick elements aligned with the tube axial direction with one element per ply through thickness and cohesive contact for the ply interface and (ii) a fibre-aligned mesh was generated, with elements aligned with the fibre orientation in each ply and cohesive contact interactions used to bond layers with dissimilar meshes.

2 Experimental Work

2.1 Specimen configuration

The tubes were made from unidirectional (UD) Hexcel IM7/8552 prepreg and manufactured by placing manually laid prepreg strips cut at the desired orientations on a filament winding core. Tubes were prepared with a $[+45_4/-45_4]_{2s}$ stacking sequence. The nominal ply thickness was 0.125 mm and the ply orientations are given with respect to the tube axis direction. All tubes were manufactured to the same base geometry shown in **Fig. 1** (a), with a tube length of 100 mm, inner diameter of 40 mm, and outer diameter of 48 mm. To ensure the quality of the tubes, the laminates were vacuum compacted every eight plies to reduce voids and the winding core was vacuum bagged before autoclaving with the curing cycle recommended by Hexcel. Finally, the tubes were scanned after the manufacturing process using a CT scan to asses the quality of the specimens, such as the lack of major defects and homogeneous wall thickness, showing no major concerns. The tubes were then machined to the specified length using a water-cooled diamond disk saw and were prepared with 45° chamfers machined on the inner edge of the tubes at the impacted end, as shown in **Fig. 1** (a). Four repetitions were performed (n=4).

2.2 Experimental setup and data reduction

The experiments were carried out in a drop-weight test rig, shown in **Fig. 1** (b), with a 10 kg steel impactor from an initial height of approximately 5.1 m to produce an impact velocity of around 10 m/s. The drop height was verified before each test using a laser extensometer and a Photron high-speed camera was used to record the failure process and track impactor displacement using DIC at 40,000 fps, with a field of view of 384x584 pixels at a 4.5

pixels/mm resolution. To allow for tracking via DIC, both the impactor and specimens were painted with a black on white speckle pattern, as shown in **Fig. 1** (c).
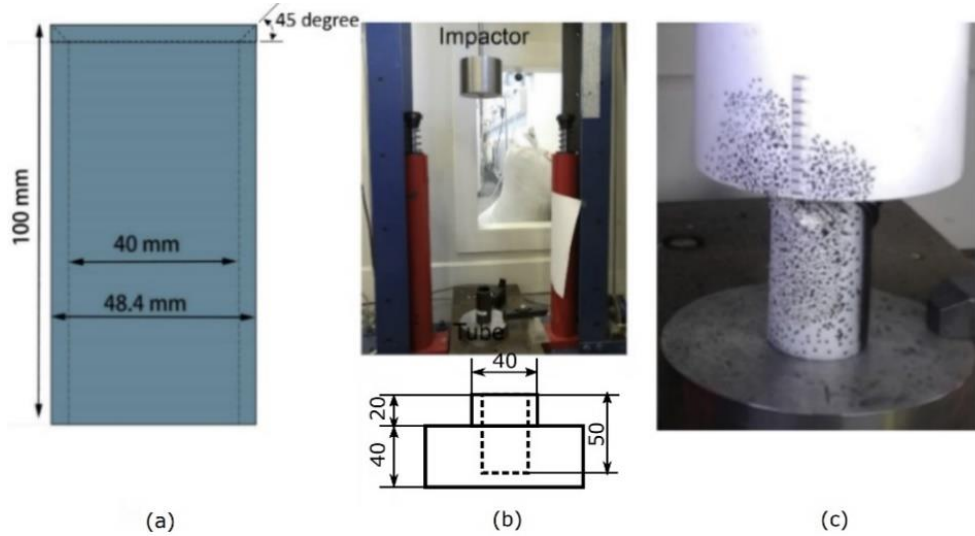

Fig. 1. (a) Nominal crush tube geometry with inner chamfer; (b) Drop-weight rig showing specimen, support, and impactor, (c) Speckle pattern on impactor and specimen used for DIC analysis

Finally, the tubes were fitted onto a specially designed steel support with a 40 mm diameter insert, **Fig. 1** (b) to fix the base of the tube in place during the test and the drop weight was released. For each specimen, the projectile displacements throughout the test were calculated using DIC and were used to verify the initial impact velocity and extract force-displacement curves by using $F = ma$ with the mass of the impactor and the acceleration, approximated by differentiation of the displacement history.

2.3 Results

The obtained force-displacement curves for the four replicates are shown in **Fig. 2**. The experimental data are shown with a frame rate/frequency of 40,000 fps. The $[+45_4/-45_4]_{2s}$ tests showed some variability, although the reason for this was not clear. Other than the variability in the total displacement, the force-displacement curves for each replicate showed similar behaviour, with a significant drop-off after the initial peak force followed by relatively stable propagation. The noise observed in the force-displacement curves after the initial drop-off was mostly an artifact of the differentiation, the underlying trend revealed by smoothing the curves would show a relatively stable propagation force between approximately 50% and 60% of the peak.
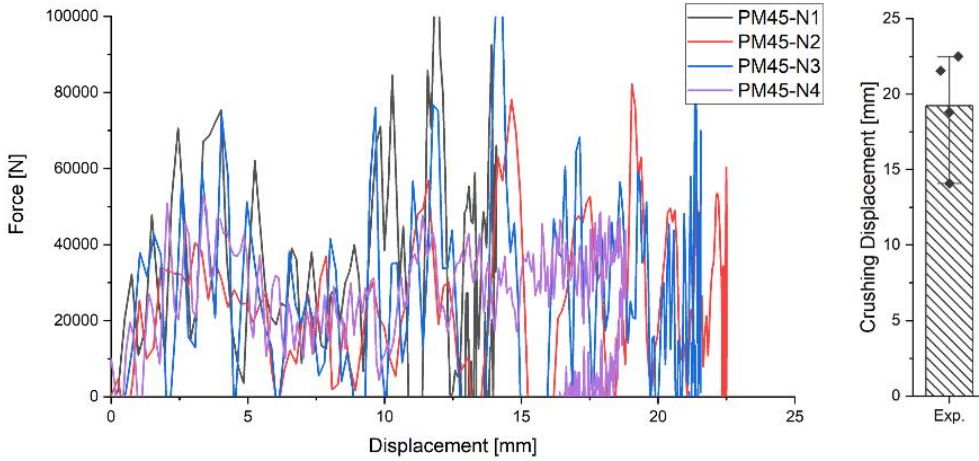
Fig. 2. Experimental force-displacement curves (left) and total crushing displacements (right).

3 Numerical Modelling

Finite element simulations were performed to predict the damage response of the composite crush tube. A ply-by-ply analysis of the CFRP tube was performed using continuum damage mechanics (CDM) to model the damage evolution within the plies. The interlaminar response, on the other hand, was modelled by means of a general mixed mode cohesive zone method (CZM) coupled with frictional behaviour. In addition, element erosion was used to remove fully-damaged elements and simulate crack formation in the material. However, it is worth mentioning that this could introduce some disadvantages in crushing simulations. These will be briefly mentioned in section 3.2. The models were validated by comparing the predicted force-displacement response and the competition of the different damage mechanisms with the experimental tests. Both Abaqus/Explicit and LS-DYNA were used to carry out the numerical simulations.

3.1 Kinematic modelling procedure

In order to optimise the number of elements the mesh of the crush tube was divided into three regions as seen in **Fig. 3**. The impacted section of the tube was modelled with a fine (0.2 mm x 0.4 mm solid elements), using fibre-aligned mesh strategy with one element per ply group. To maintain the quality of the mesh in the chamfer, the maximum number of plies lumped together was four, thus limiting the element thickness to 0.5 mm and yielding a mesh with eight layers. The structured-aligned mesh was generated by applying cylindrical transformations using Abaqus-scripting. At the base of the tube, away from the impact, the orthotropic layers are assumed to behave elastically and are modelled by regular-coarse solid elements (1 mm x 1mm). Between both sections, a transition region without allowed damage is used to connect the fibre-aligned mesh to a coarse region avoiding unrealistic stress concentrations. Both regions are kinematically constrained using surface-base tie formulations to enforce continuity of displacements and rotations across their boundaries.
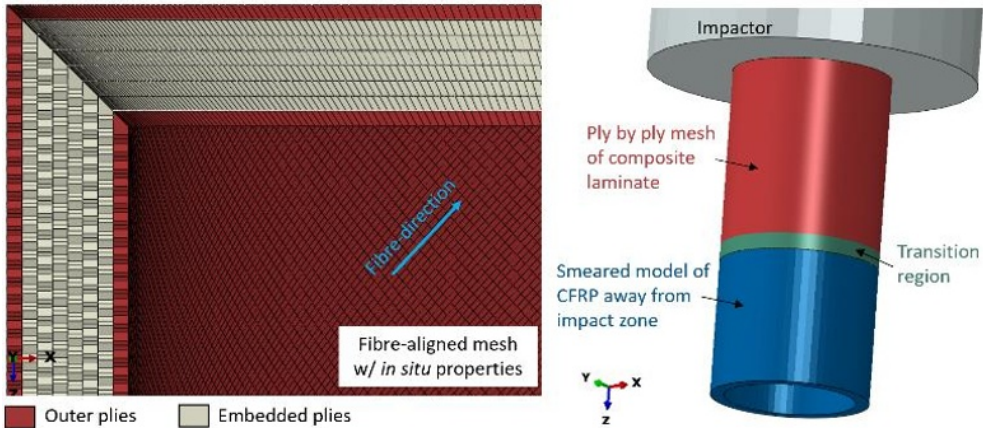
Fig. 3. Meshing strategy and fibre-aligned mesh of the composite crush tube.

3.2 Constitutive modelling

For unidirectional ply behaviour, the intralaminar damage in ABAQUS is modelled using a thermodynamically consistent CDM implemented in a VUMAT user subroutine [5, 6]. This code is able to predict the gradual reductions of the elastic stiffness and strength properties and simultaneously guarantee the appropriate energy dissipation through different failure modes taking into account *in-situ* ply properties. In parallel, a pressure- and rate-dependent plasticity and damage model [7], calibrated using quasi-static (QS) and high-rate (HR) properties, was implemented as a UMAT for use in LS-DYNA. Since node sharing is not typically permitted with a fibre-aligned mesh, the surface-based cohesive contact formulation was used to model the interlaminar damage. For the interlaminar damage, in both Abaqus and LS-DYNA the native surface-based cohesive zone model (CZM) implementations were used. The QS and HR material properties for the homogenised UD plies and the interface were adopted from [8].

3.3 Results

Using traditional meshing techniques, matrix damage struggled to follow physically-observed crack paths along the fibre direction, instead tending towards more diffuse damage and excessive element distortion ahead of the impactor. By combining both physically based constitutive damage models and suitable modelling techniques, not only the proper kinematic simulation of damage is guaranteed but also the highly nonlinear laminate response of different failure mechanisms is realistically simulated in line with the experimental observations. The simulated fracture morphologies are qualitatively compared with experimental images taken 0.9 ms after impact in **Fig. 4**. With a fibre-aligned mesh and the element erosion technique, the cracks are observed to propagate along the fibre-direction as seen in the physical experiments. However, the crack length appears to be underpredicted for the Abaqus model, while the LS-DYNA model appeared to predict excessive bulging of the cracked plies.
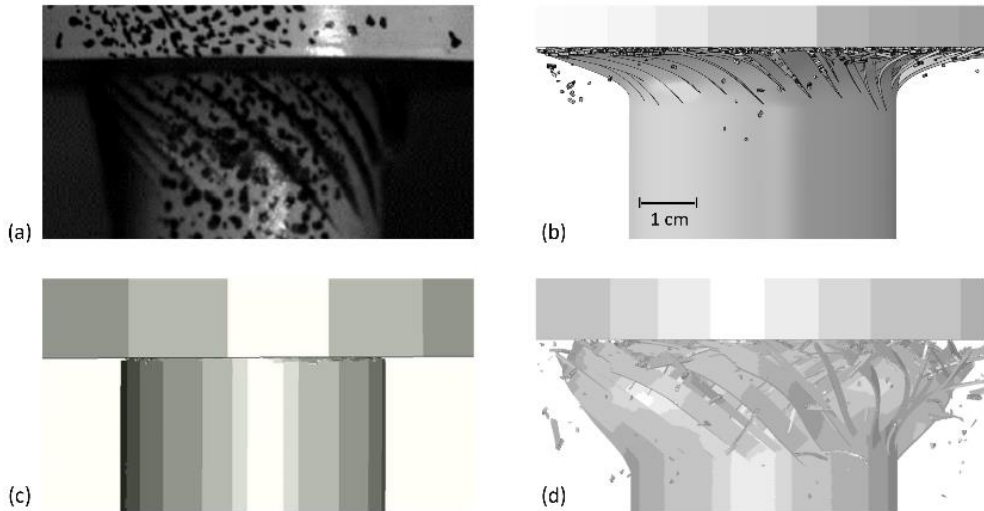
Fig. 4. Damage morphology in a $[+45_4/-45_4]_{2s}$ specimen after 0.9 ms. (a) Experimental. (b) Abaqus (fibre-aligned mesh). (c) LS-DYNA (regular mesh). (d) LS-DYNA (fibre-aligned mesh).

The predicted force-displacement curves are compared with experimental measurements in **Fig. 5**. From the numerical results, the drops in the reaction force leading up to the maximum peak force that were observed in the experiments can be attributed to the onset of delamination at each of the ply interfaces. After the peak load, once the crash front has passed the chamfer and all ply interfaces are in delamination, the crushing response is dominated by intra-ply matrix splitting along the fibre direction and inter-ply delamination. While the initial response of the simulations using an aligned mesh correlates well with experimental measurements, the force can be underpredicted during stable crushing. The force predicted with the regular (non-aligned) mesh remains elevated during later stages of crushing, which is in agreement with experimental measurements. Related to the peak load prediction, it is important to consider some issues associated with the element erosion technique. Although element erosion can avoid excessive element distortions and subsequent numerical problems, this approach can also introduce undesired loss of mass and potentially available energy from the system. In the particular case of crushing simulations element erosion could introduce poor load bearing capability mainly during contact interactions. In order to guarante a balance for both crack representation and accuracy load prediction, a deformation gradient parameter was established as criteria for element erosion [5].
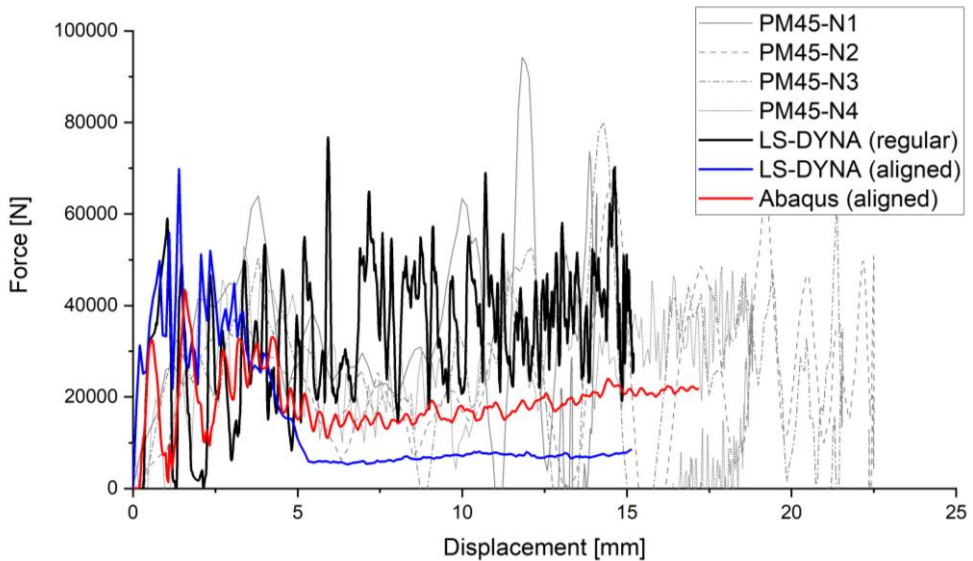
Fig. 5. Predicted load vs. displacement curves compared with experimental measurements.

4 Conclusions

The present study describes a high-fidelity numerical model for analysing the dynamic crushing response of an angle-ply composite crush tube. The predicted force-displacement curves and damage mechanisms were compared with experimental results. The amount of matrix cracking is not insignificant and an accurate reproduction of intra-ply damage, such as the number of matrix cracks and their propagation, can also be very important for the accuracy of the model. The results are clearly mesh-dependent for both material models, even if reasonable predictions of the force-displacement are possible with rate-independent material properties and even coarse non-aligned meshing, as long as the interface properties and energy release rates are adequately calibrated. However, the use of non-aligned meshing fails to produce the failure mechanisms observed in the experiments.

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