Meso-scale Modeling of Carbon Fiber Composites for Crash Simulation

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Abstract

Typical compression molded laminated carbon fiber composites are made of stacked UD, woven and/or braided carbon fiber pre-pregs oriented differently through the thickness. Resulting micro-structure (layering, anisotropy, inhomogeneity, etc.) is quite complex and greatly affects their mechanical responses. In particular, crash characteristics of CF composites are quite complex and are dominated by both intra-laminar and inter-laminar failure modes such as matrix failure, fiber breakage, fiber buckling, delamination, etc. Despite a large number of constitutive models available in commercial codes, crash simulation of composites is still extremely challenging. This is primarily due to the inadequacy of current macro-scale modeling in characterizing complex micro-structural failure modes during crash.

The core issue is the physical scale of failure/damage mechanisms in composites that tend to be smaller than the mesh size of typical macro-scale FEA model. The mismatch in scales can limit the accuracy of composite material failure/damage simulation even when advanced constitutive models are used. This study focuses on using a meso-scale modeling approach for carbon fiber composites for improved characterization of failure/damage. Axial crushing of a square CF composite tube is chosen for testing and analysis to demonstrate the effectiveness of meso-scale modeling. Comparison of simulation results from LS-DYNA® with test shows remarkable accuracy achieved in meso-scale modeling. While significant computation time is necessary for the meso-scale modeling and analysis, the approach is invaluable to characterize and understand the detailed failure/damage modes in composites during crash.

Introduction

Pre-preg compression molded (PCM) CF composites have high strength-to-weight ratio compared to any metals including aluminum and magnesium. Specific energy absorption (SEA) of CF composites is one of the highest among all lightweight material systems and therefore an excellent material for absorbing crash energy. Because of that, CF composites are excellent material option for the primary energy structure a vehicle. In addition, CF composites are corrosion resistant and the manufacturing process provides an excellent avenue for part consolidation saving critical assembly time and cost. As such, CF composites are being increasingly used for the design vehicle body structure.

Typical laminated PCM CF composites are made of UD, woven and braided CF pre-preg plies. Due to fiber direction, each ply is anisotropic on its plane. As such, when the plies are stacked up, they are orientated differently to achieve required overall laminate strength characteristics. In current crash simulation modeling practice, typically composite parts are modeled using single thin or thick through the thickness shell elements as shown in Fig. 1. Multiple through the thickness integration points are used to account for the laminated characteristics for thin shell elements and thick shell elements.

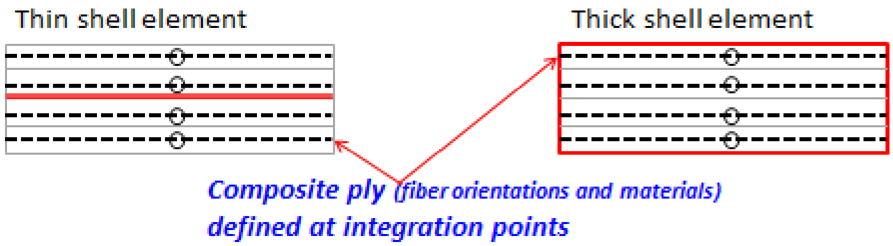

Fig. 1 Shell Model for Composite

The advantage of this approach is that it is easy to use as it is similar to model structural components made out of metals. However, this approach cannot model properly some key CF damage characteristics. It cannot represent inter-ply shear deformation modes and properly characterize inter-ply delamination. Ultimately, single shell model cannot capture the large geometric deformation when a single layer of carbon fiber part splits and breaks into multiple layers and pieces. The logical modeling approach to capture comprehensively the damage physics is multiple layers and small mesh size - 'meso-scale modeling'. The meso-scale modeling can generate large FEA model, which will require substantial computation power to calculate.

Take an example of a body part made with carbon fiber composite with significant potential structural load. Its typical thickness is about 3 to 4mm. To capture intra-ply failure characteristics, the element size is 2-4 mm. If one assumes 20 plies and average shell element size of (say) 3 mm, one would require ~1 million shell elements and about the same number of cohesive elements i.e. ~ 2 million elements. If a multiple CF composite body structure components are to be included, vehicle model size can easily exceed 20 million or more. Besides model size, the contact definitions for these elements are also different from typical crash models since contact between the stacked shells is activated when delamination occurs during a simulation. Note that delamination is controlled by the failure of the cohesive layers. The large model size and non-traditional contact events affect scalability and efficiency of computation. Despite the demanding computation resources, meso-scale modelling is required to characterize such complex delamination processes and truly predict crash response.

Meso-scale Model Development

In meso-scale modelling, we model each ply in the laminate using thin or thick shell elements. This amount to stacking of a number of shell elements (equaling the number of plies in the laminate) representing the laminate. Typical CF plies are 0.1 – 0.2 mm thick depending on ply type (i.e. UD, woven etc.) Typical gage for a composite part can be in the range of 2mm to 4 mm and therefore, number of through thickness plies is about 20 to 30. This requires through thickness stack up of 20 to 30 shell elements with cohesive element layers between two plies. Fig. 2 shows the two approaches for modelling: stacked thin shells elements and stacked thick shell elements. In both approaches, different fiber orientations and materials are defined at the integration points. However, the cohesive layers in stacked thin shells has thickness equals to ply thickness while the cohesive layers in stacked thick shells has zero thickness.

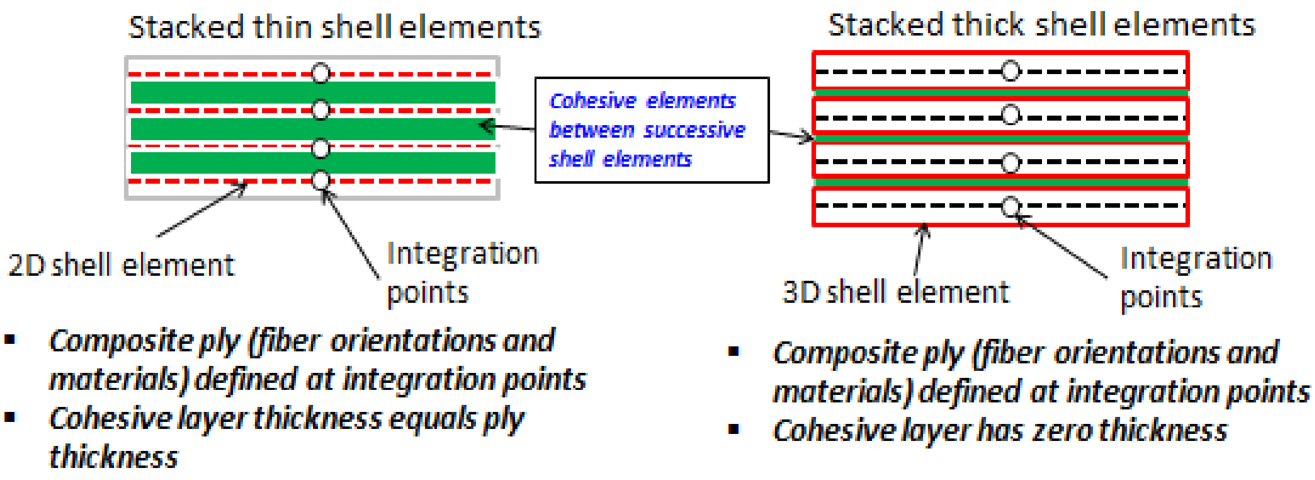

Fig. 2 Two Approaches for Stack of Shell Model

The task of creating a model using the meso-scale approach is quite formidable for complex shaped parts. Therefore, a special meshing capability was developed for the ease of mesh generation for a laminated composite structure. With additional input such as the fiber orientations and materials for each ply, the software tool can generate multiple layers model including cohesive layers based on single layer shell model.

Test Setup

For verification, a thin-walled box column with hexagonal section, as shown in Fig. 3, was prepared for axial crush test using a drop tower test setup. The hexagonal section box column was formed by adhesively joining two carbon fiber composite C-shaped channels with flanges. The channels were made from UD composite pre-preg plies with a [0/60/-60/0/60/-60]s layup for a total wall thickness of 2.4mm using compression molding. As shown in Fig. 3, the flanges of the box column have been chamfered at 45 deg angle to allow progressive crushing during impact.

Fig. 3. Sample of Composite Tube

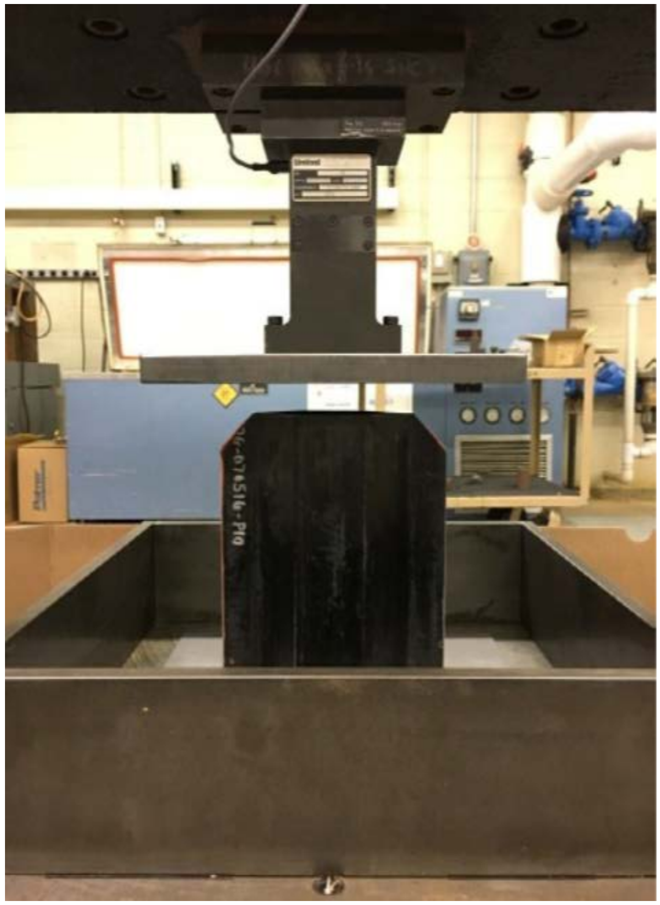

Fig. 4. Drop Tower Test

The box column was fixedly mounted at the base of the drop tower as shown in Fig. 4. The impactor with 795 Kg weight was raised to a height of 994 mm above the top edges of the box column. With this setup, the impactor reaches a velocity of 4.4m/s at the instant of hitting the top edges of the box column. The test setup details are shown in Fig. 5. Accelerometer was used to measure deceleration time response of the impactor during crushing of the box column. . Load cells are used to measure the crush load time response during the test. A stopper was mounted to prevent the impactor from crush the column excessively. . A number of tests were performed to ensure repeatability of the tests. Fig. 6 shows the post test deformed shapes of one crashed sample. As evident, the composite box column undergoes complex failure modes including fragmentation of matrix, fiber breakages, extensive inter-ply delamination, etc. during crash.

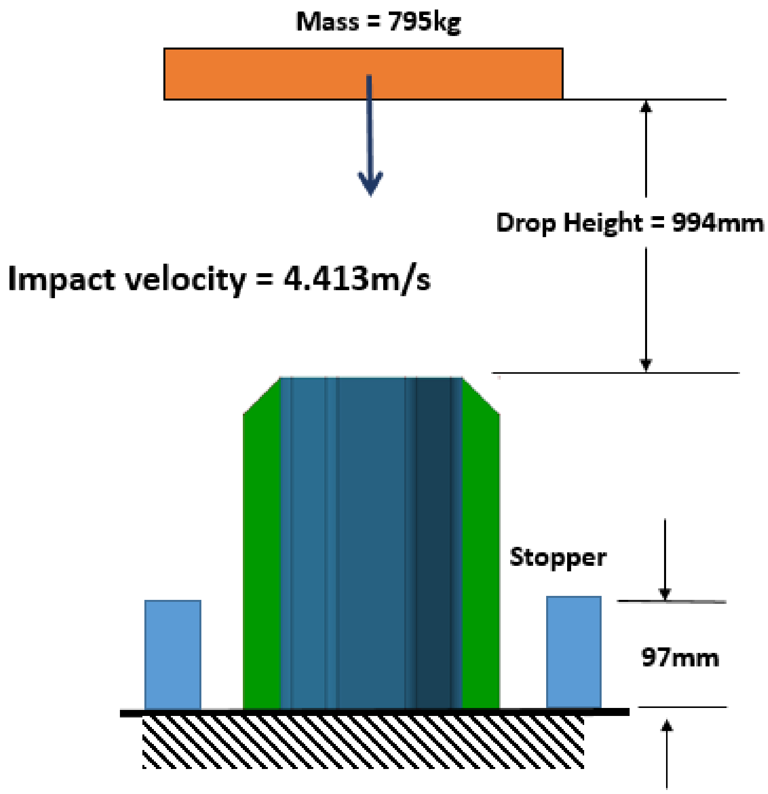

Fig. 5 Drop Tower Setup

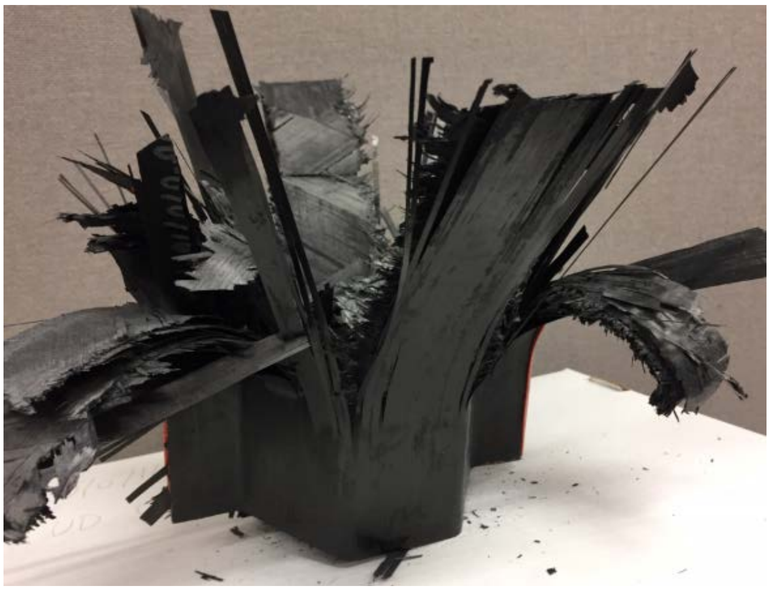

Fig. 7 Damages of Composite Tubes under Axial Impact Load

Simulation and Results

The composite model created with the software tool mentioned in previous section comprises of 1.3 million thick shell elements and approximately same number of cohesive elements as shown in Fig. 8a. The element size is one mm. Fig. 8b to Fig. 8c shows close up views to the top edge, which has a special edge treatment to act as trigger for delamination. Fig. 8b shows an expanded cross section view of the top edge. The first row of cohesive elements that separate layers of composite thick shells elements were removed. The absence of the first row of cohesive elements served as an effective trigger for delamination. MAT54 in LS-DYNA was used to model the composite material behavior.

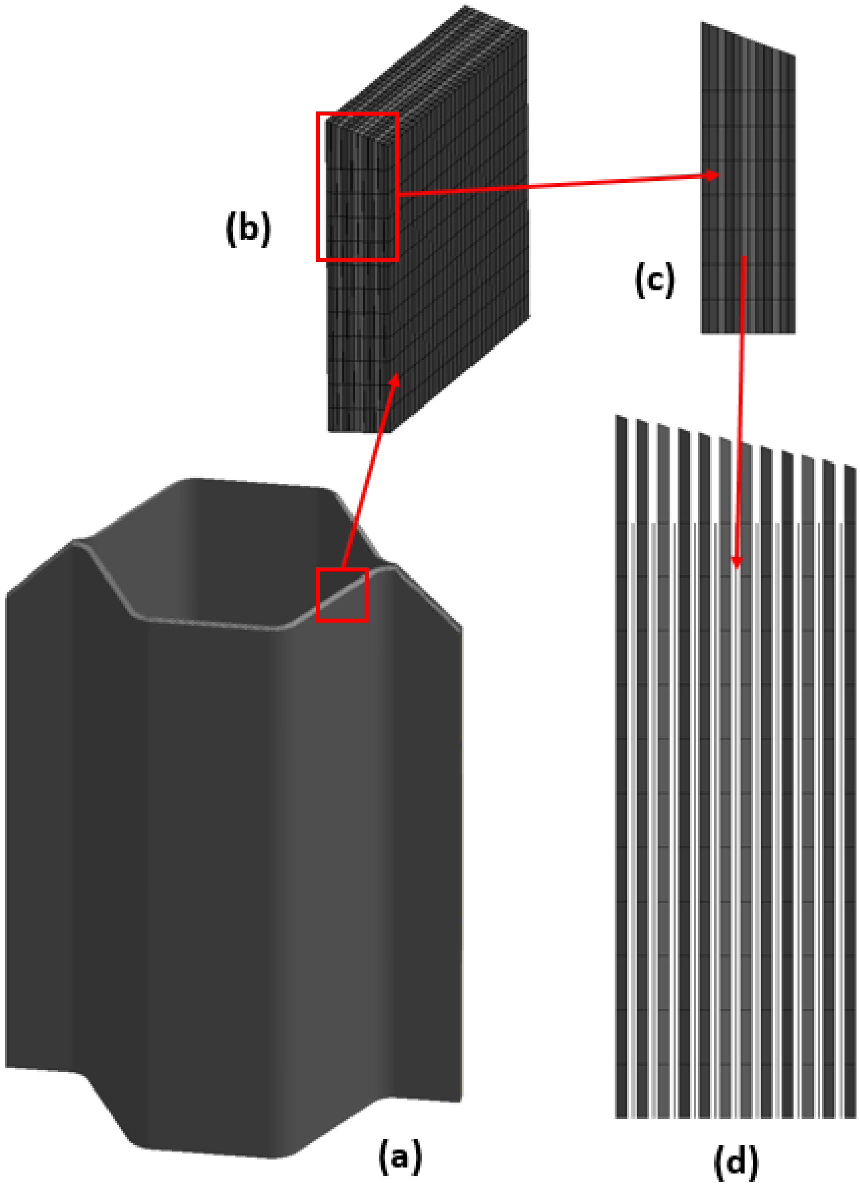

Fig. 8 Details of composite model

While the model size of 2.5 million is not large in today's standard, the element size and time step size make such calculation a very time consuming task. A single simulation required more than one week of CPU time on a 96-processor environment to finish. However, such intensive computation yields some remarkable results. Fig. 9 shows a comparison of test results and simulation results in load vs time and Fig. 10 shows a sequence of deformed shapes of the composite box section. The simulation is qualitatively and quantitatively similar to measurements and observations in test.

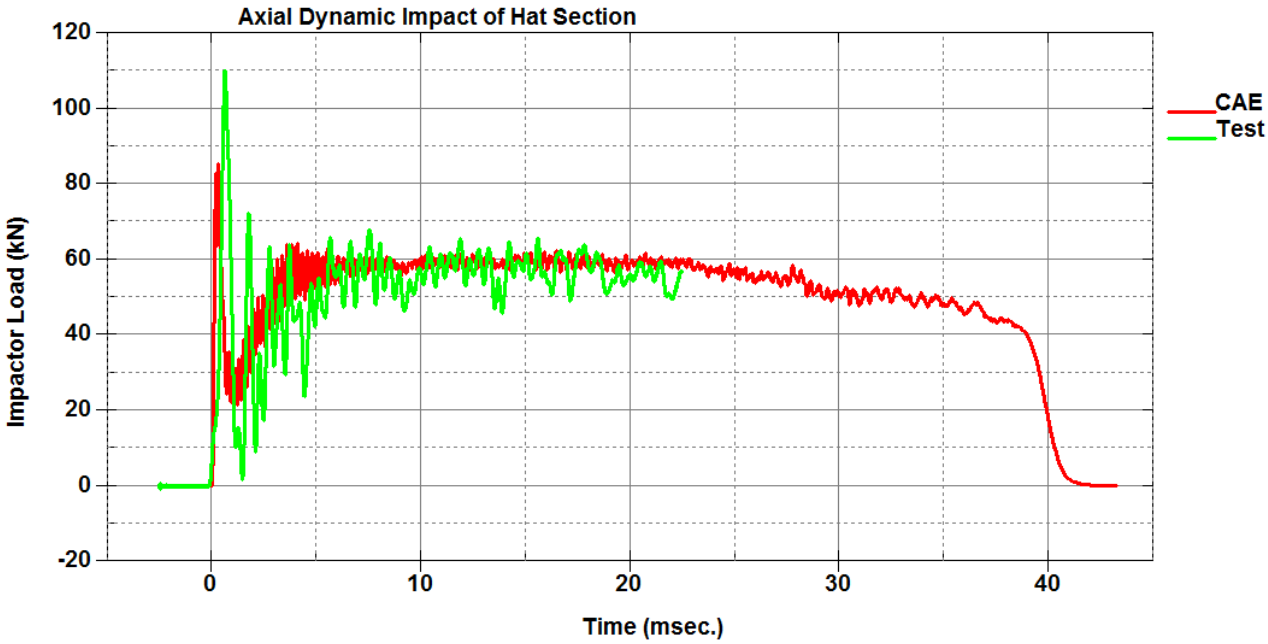

Fig. 9 Comparison of CAE and Test

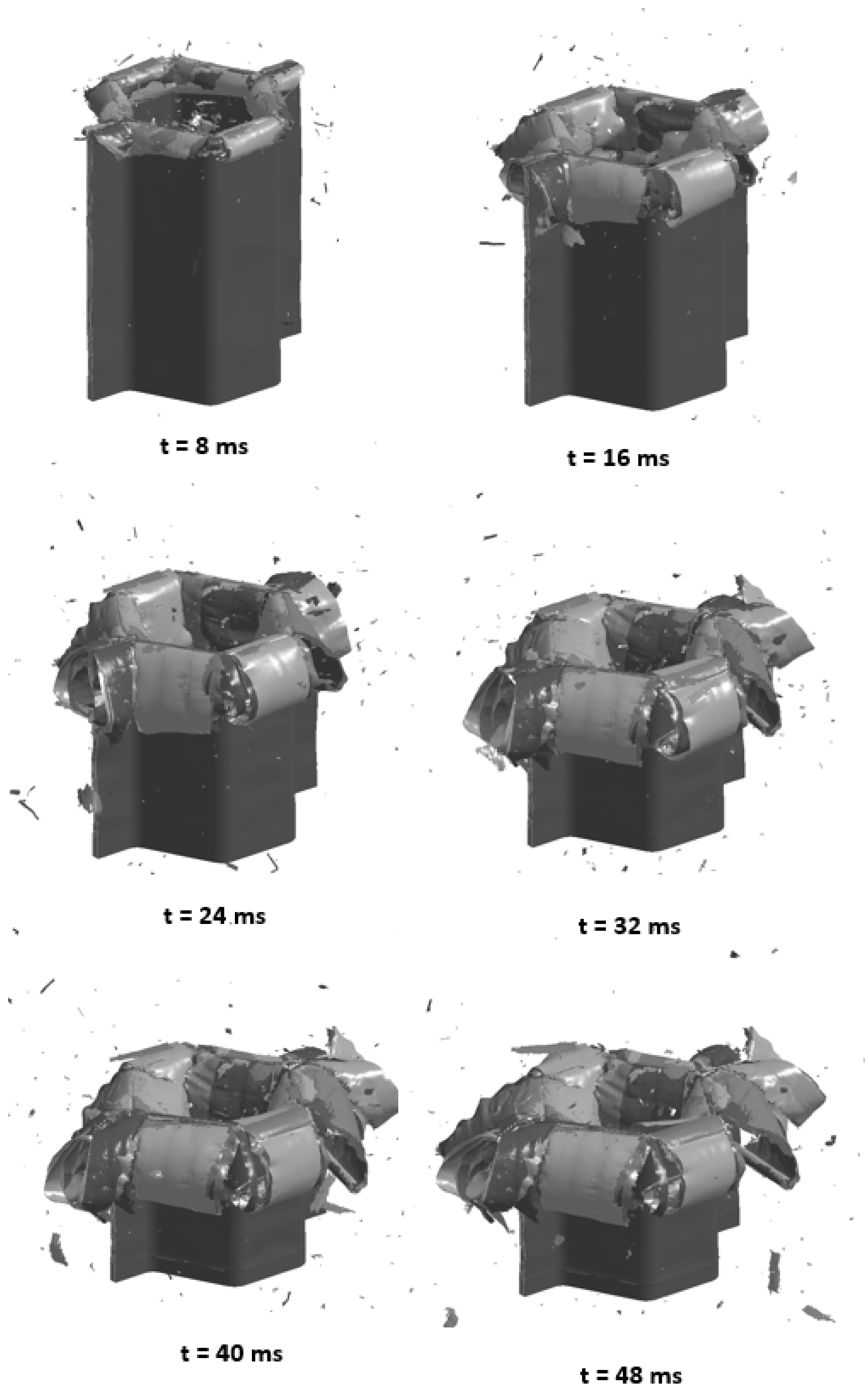

Fig. 10. Deformation Snapshots

Conclusion

Although the example problem used MAT54 which is a simplistic composite material model among many advanced composite material models available in LS-DYNA, meso scale modelling which capture fine structural details in sub ply level provides good results to a very complex axial crush example problem. While better material model can provide better representation of composite material behavior, a meso-scale model, which matches the physical scale of failure/damage mechanisms in composites, is more important to achieve correct results. This is particularly important if simulation is intended to replace physical tests. Mismatch in scales can limit the accuracy of composite material failure/damage simulation even when advanced constitutive models are used.

Acknowledgement

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