Simulation of the Quasi-static Crushing of a Fabric Composite Plate
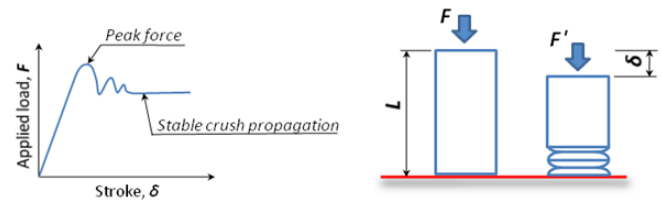

Acknowledgement

Summary

Composite structures often have a higher capacity for absorbing energy than their metal counterparts. The crushing behavior of composite materials is complex, and the inclusion of composite components in vehicles for crash protection can necessitate expensive experimental testing. The ability to computationally simulate the crushing response of composite structures can significantly shorten the product development cycle and reduce cost in the aerospace, automotive, and railway industries.

In this Technology Brief, we describe a methodology for modeling the crushing behavior of composite structures using Abaqus/Explicit. Very good quantitative and qualitative agreement between the numerical results and experimental data is shown, demonstrating the utility of Abaqus/Explicit for assessing the crashworthiness of composite structures and reducing the amount of costly experimental testing.

Background

Occupant protection systems play a crucial role in preventing severe injuries and fatalities during vehicle crashes. As a result, the evaluation of crashworthiness is an important stage in the design of contemporary aircraft and ground vehicles. The use of composite structures as energy absorbers is rapidly growing in the aerospace, automotive, and railway industries because composites exhibit a significantly higher energy absorption capacity per unit weight than metals. Energy-absorbing composite components, which are usually designed to dissipate kinetic energy under controlled collapse, substantially increase structural crashworthiness in exchange for a reasonable increase in overall vehicle cost.

Traditionally, the development of crashworthy designs has relied upon time consuming, expensive experimental testing. However, carrying out a meaningful experimental program during the initial design stages is not practical. Thus the ability to accurately simulate the crushing and energy absorption response of composite structures can significantly shorten the product development cycle and reduce cost.

Key Abaqus Features and Benefits

- Constitutive model for fabric reinforced composites that accounts for progressive in-plane stiffness degradation due to fiber/matrix cracking

- Continuum shell elements can discretize the volume of the plate or the individual plies, allowing for detailed through-thickness modeling

- Surface-based cohesive behavior within the Abaqus/Explicit general contact framework allows for the simulation of delamination

When crushed, composites absorb energy through a combination of interlaminar (delamination) and intralaminar (in-plane) fracture mechanisms. The complex physical processes require an advanced analysis capability offering suitable material models and a robust progressive damage framework. Abaqus/Explicit is an ideal tool for this class of analyses.

The simulation presented here examines the crushing response of a carbon/epoxy fabric composite plate specimen. A physics-based approach that accounts for both in-plane and delamination failure mechanisms is used. The in-plane response of the fabric plies is modeled using a constitutive model for fabric-reinforced composites that is available as a built-in user subroutine (VUMAT), whereas delamination is simulated using the cohesive surface capability.

The composite plate under consideration is corrugated (Fig. 2) and was developed and tested by the Crashworthiness Working Group of the CMH-17 organization. During a recent round-robin effort, a series of crush tests on this specimen was performed and the test results were made available to participants [2].

The test specimens were manufactured with the TORAYCA T700/2510 carbon/epoxy fabric material system

[1]. The [0/90]$_{2S}$ lay-up was 2 mm (0.079 in.) thick. To facilitate stable crushing, a single-sided 45-degree chamfer was machined at the bottom end of the cured specimen. Each specimen was 76.2 mm long (3 in.) and 50.80 mm wide (2 in.). Because they are self-supporting, the specimens were tested in the vertical configuration standing free on an as-milled dry steel surface. The testing was performed at a quasi-static rate of 0.2 mm/sec (0.5 in/min).

Analysis Approach

The geometry of the plate was created in Abaqus/CAE and is shown in Figure 3; the crush initiating chamfered edge is clearly visible. Each of the eight fabric plies was individually meshed with continuum shell elements (SC8R). A uniform element density with size of 1 mm by 0.5 mm (0.04 in. by 0.02 in.) was used. Continuum shell elements have the geometry of a three-dimensional solid but their kinematic and constitutive behavior are similar to those of conventional shell elements. This type of element allows for the accurate modeling of a stack of composite plies. The finite element model had approximately one-half million degrees of freedom.
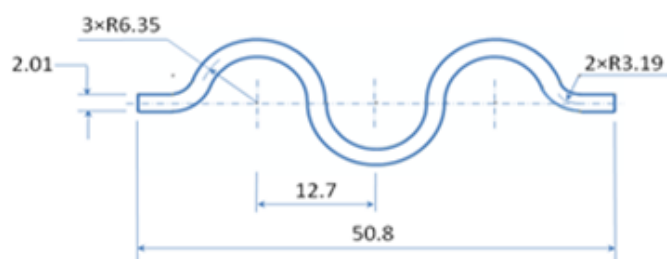

Figure 2: Schematic of the corrugated fabric composite panel (all dimensions in millimeters).

In-plane Response of the Plate

The in-plane response of the fabric plies was simulated with the constitutive model for fabric reinforced composites that is available as a built-in user subroutine (VUMAT). An individual ply is modeled as a homogeneous orthotropic material that is capable of sustaining progressive stiffness degradation due to fiber/matrix cracking and plastic deformation under shear loading. This model requires the input of the elasticity constants, damage initiation coefficients, damage evolution coefficients, and shear plasticity coefficients. The elasticity constants include the Young's moduli in the fiber directions, the principal Poisson's ratio, and the in-plane shear modulus. The damage initiation coefficients include the tensile and compressive strengths along the fiber directions and the shear strength at the onset of shear damage.

The elasticity constants and fiber strengths are usually obtained from standard uniaxial coupon tests of 0/90 laminates; for the present analysis, these data were obtained from the Crashworthiness Working Group [2]. The damage evolution coefficients along the fiber directions are represented by the tensile and compressive fracture energies per unit area that can be measured experimentally as described in [3]. For the present simulation, average values of the fracture energies for similar material systems from [3] were utilized.
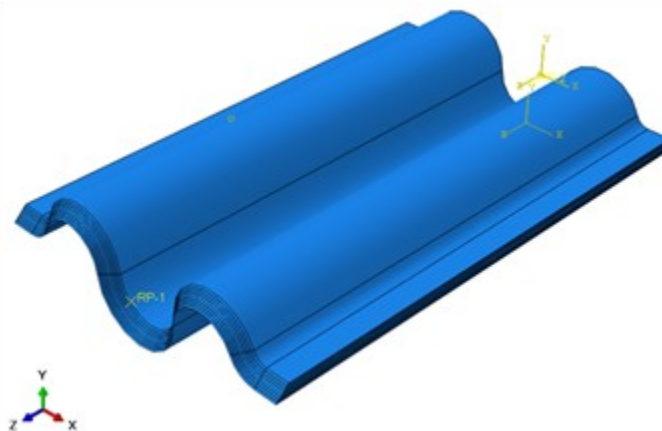

Figure 3: Abaqus/CAE model of the corrugated fabric composite plate

The calibration of the shear response parameters, i.e., the damage evolution coefficients and shear plasticity coefficients, is usually based on the results of cyclic tensile tests for ±45° laminates (refer to SIMULIA Answer 3749 for a description of the calibration procedure). In the present analysis, these shear response parameters were adopted based on the calibration results for similar material systems. Because shearing of the fabric ply is not a dominant failure mode for this analysis, the use of typical values for the damage and plasticity shear material parameters do not have a perceptible influence on the results.

Interlaminar Response of the Plate

The surface-based cohesive contact capability was used to model the delamination phenomenon. Damage initiation at the interfaces was defined using the quadratic nominal stress criterion. Typical values of the interface damage initiation properties are available in the literature. Progression of damage at the interfaces was modeled using the critical mixed mode energy behavior based on the Benzeggagh-Kenane (BK) law. The values of the required normal and shear mode critical fracture energies were obtained from the Crashworthiness Working Group [2]. After damage initiation, the evolution of the damage variable until final failure was modeled using an exponential softening law.

Element Deletion

Failed continuum shell elements must be removed from the model. In the present work, damage-based element

deletion is combined with a deformation-based deletion criterion. Detached parts of the fabric composite plies are removed from the model to avoid premature termination of the analysis. The detached parts are deleted when they move out of the range of a three-dimensional box that is defined by user subroutine VUSDFLD.

Loads and Boundary Conditions

The composite plate was positioned vertically on a rigid plate, which was modeled using conventional shell elements. The crushing load was applied to the composite plate through another rigid plate moving with a constant velocity of 200 mm/sec (470 in/min). This artificial increase of the loading velocity has no effect on the analysis results; dynamic effects only become significant beyond a velocity of 500—1000 mm/sec (1200—2400 in/min).

The contact interactions between the debonded composite plies and between the composite plies and the test rig were modeled using the general contact capability of Abaqus/Explicit. After delamination occurs, the general contact definition is automatically updated to account for possible post-delamination contact.

Mass Scaling

The mass of the composite plate was increased by three orders of magnitude at the beginning of the analysis using fixed mass scaling. Similar to the artificial increase of the loading velocity, this was employed to achieve a reasonable runtime. A comparison between the kinetic and strain energies confirmed that the quasi-static character of the problem was not changed.

Results

The deformed shape of the corrugated plate at the end of the crushing simulation is shown in Figure 4. Note that the deletion of damaged elements in the plies creates detached parts that are removed from the model as explained previously. Figure 4 shows that the simulation reproduced important characteristic features of the crushing response of composites, such as frond formation, propagation of delamination, and the accumulation of debris between the test rig and plate.

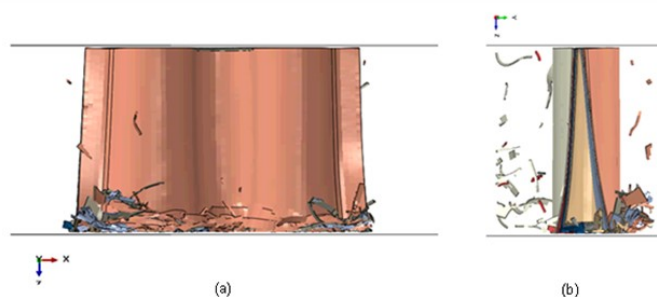(a)   (b)

Figure 4: Simulated deformed shape of the corrugated composite plate (a): front view (b): side view
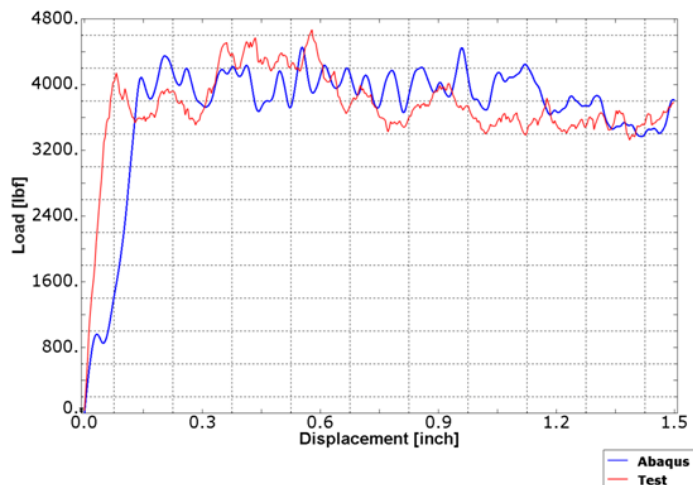

Figure 5: Experimental and predicted load-displacement curves

A close match between the experimental [2] and simulated load displacement curves is demonstrated in Figure 5. Both the peak and average crush forces (stable crush propagation) were predicted accurately. It can be seen from the figure that the height of the crushed plate was reduced by half with respect to its undeformed configuration.

The ability of a material to dissipate energy is usually characterized in terms of its specific energy absorption (SEA). The experimental and simulated SEA of the corrugated plate is shown in Figure 6. The results agree well, especially in the second half of the crushing process. The largest discrepancy is observed at the early loading stages during the crushing of the chamfered edge of the plate. The overall correspondence between the measured and simulated SEA curves is good, considering the extremely complicated nature of the crushing process.
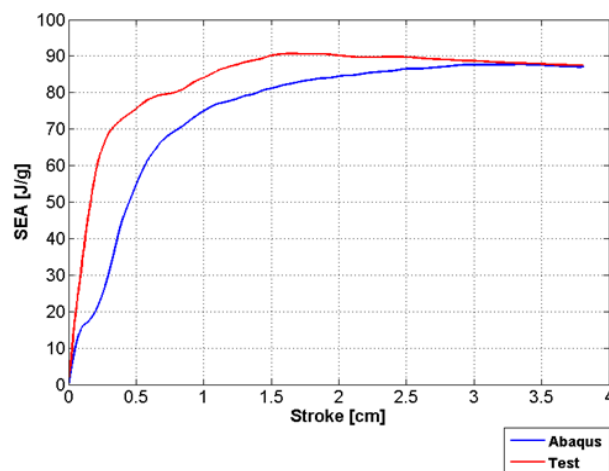

Figure 6: Experimental and numerical specific energy absorption

Conclusions

The results of an Abaqus/Explicit simulation of the quasi-static crushing response of a corrugated fabric composite plate show very good quantitative and qualitative agreement with experimental data, demonstrating that the proposed methodology and tools provide realistic crush simulations of composite structures. The use of Abaqus/Explicit to assess the crashworthiness of a composite structure can replace costly experimental testing.

References

1. Feraboli, P., "Development of a Corrugated Test Specimen for Composite Materials Energy Absorption," *Journal of Composite Materials*, Vol. **42**, No. 3, 2008.

2. Test results of the Crashworthiness Working Group of the CMH-17, *Private Communications*.

3. Pinho, S.T., Robinson, P., and Iannucci, L., "Fracture Toughness of Tensile and Compressive Fibre Failure Modes in Laminated Composites," *Composites Science and Technology*, Vol. **66**, No. 13, 2006.

SIMULIA References

For additional information on the Abaqus capabilities referred to in this brief please see the following Abaqus Version 6.10 documentation references:

- Analysis User's Manual
  - 'Continuum shell element library,' Section 26.6.8
  - 'Surface-based cohesive behavior,' Section 33.1.10
- 'VUMAT for fabric reinforced composites,' SIMULIA Answer 3749