Validating Predictive Modeling of Carbon Fiber Composites
In Automotive Crash Applications

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In this reporting period, the following tasks have been attempted:

Task 13.0  Select commercial models and model components from public domain
Task 13.1  Select progressive crash models in commercial codes
Task 13.2  Select progressive crash models from public domain

1. Task 13.0  Select commercial models and model components from public domain
   & Task 13.1  Select progressive crash models in commercial codes

Composite materials models are available in commercial explicit Finite Element (FE) packages such as LS-DYNA, PAM-CRASH, RADIOSS, and ABAQUS. All composite models are based on an orthotropic elasticity framework. They differ in the failure criterion and the manner that properties are degraded upon failure. The two common types of degradation laws are the progressive failure and damage mechanics based damage evolution.

Table 1 presents a survey of the FE codes used by major automakers in crashworthiness design in 2012. As shown, LS-DYNA has been adopted by most of the automakers. PAM-CRASH is used by European aerospace industry. It has considerable activities in composite component crash simulations. ABAQUS is widely used by the research community, particularly by academic users. Newly developed composite models are often implemented in ABAQUS first. RADIOSS is still used by Ford and Renault/Nissan. In recent years, some users have switched from RADIOSS to other codes.

Table 1. The FE codes used in crashworthiness design by major automakers

<table>
<thead>
<tr>
<th>Automaker</th>
<th>Crash code</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Motors</td>
<td>LS-DYNA</td>
<td></td>
</tr>
<tr>
<td>Chrysler</td>
<td>LS-DYNA</td>
<td></td>
</tr>
<tr>
<td>Ford</td>
<td>RADIOSS/LS-DYNA</td>
<td>Car/Truck</td>
</tr>
<tr>
<td>Toyota</td>
<td>LS-DYNA</td>
<td>used RADIOSS prior 2012</td>
</tr>
<tr>
<td>Honda</td>
<td>LS-DYNA</td>
<td></td>
</tr>
<tr>
<td>BMW</td>
<td>LS-DYNA/ABAQUS</td>
<td>Evaluated ABAQUS</td>
</tr>
<tr>
<td>Daimler AG</td>
<td>LS-DYNA</td>
<td>Evaluated ABAQUS</td>
</tr>
<tr>
<td>Renault/Nissan</td>
<td>RADIOSS</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Composite material models in LS-DYNA

<table>
<thead>
<tr>
<th></th>
<th>brick</th>
<th>shell</th>
<th>Degradation Law</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td></td>
<td></td>
<td>Composite Damage</td>
</tr>
<tr>
<td>54/55</td>
<td>✓</td>
<td>✓</td>
<td>Progressive failure</td>
</tr>
<tr>
<td>58/158</td>
<td></td>
<td></td>
<td>Laminated Composite</td>
</tr>
<tr>
<td></td>
<td>✓</td>
<td></td>
<td>Damage</td>
</tr>
<tr>
<td>59</td>
<td>✓</td>
<td>✓</td>
<td>Composite Failure</td>
</tr>
<tr>
<td>161/162</td>
<td></td>
<td>✓</td>
<td>Progressive failure</td>
</tr>
</tbody>
</table>

1.1 LS-DYNA

Table 2 is a summary of the composite material models in LS-DYNA and the types of element the models support. Among the eight models shown in Table 2, MAT54/55 [1-3], MAT58 [4-6], and MAT162 [7,8] are commonly used in crash/impact simulations.

MAT54/55 (Enhanced Composite Damage) is available only for shell. MAT54/55 is a progress failure model. Its failure surfaces and degradation rules are summarised in Table 3. The variables and their typical values for a unidirectional carbon/epoxy are listed in Table 4.

MAT58 (Laminated Composite Fabric) is also available only for shell. The failure criteria for MAT58 were not provided explicitly in the manual. The users are given the choice to select either a faceted or a smooth (quadratic) failure criterion, which is assumed as Hashin or Tsai-Wu types. MAT58 is based on damage mechanics. It employs an exponential damage evolution law

\[ \omega_i = 1 - e^{-(\frac{\varepsilon}{\varepsilon_0})^{n}} \]  

(1)

MAT158 (Rate Sensitive Composite Fabric) allows the consideration of rate dependence in the shear direction through defining a relaxation modulus in the form of Prony series. Otherwise, it is identical to MAT58.

It is difficult to obtain progressive crash with shell elements. To simulate the progressive crash behavior, a SOFT parameter is introduced in composite models in LS-DYNA that allows a predefined percentage reduction in strength for elements being exposed to the crush front [5]. Adjusting the value of SOFT has been used as a mean to obtain the desired response [1,3,9]. Figure 1 shows an example. As seen, three values of SOFT were used for components of three different shapes: 10% for a C-channel, 20% for a Hat-stiffener, and 15% for an Angle [9]. This practice is rather common in composite crash simulations.

Modeling the initial contact between the composite component and impact platen is another art. In LS-DYNA, defining a contact penetration curve to soften the impulse upon impact has been proven to be critical in obtaining progressive crash for certain components [10]. Figure 2 shows an example of user defined contact penetration curve. It also compares two simulations.
performed with and without a contact penetration curve [9]. Without the contact penetration, the response was discontinuous with spikes of large value. With the contact penetration, a continuous response was generated. After filtering, the response was more like what was seen in the experiment.

Table 3. MAT54/55 failure criteria and degradation rules

<table>
<thead>
<tr>
<th>Description</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber tensile</td>
<td>$e_f^2 = \left( \frac{\sigma_{11}}{X_T} \right)^2 + \beta \left( \frac{\sigma_{12}}{S_c} \right) - 1 &gt; 0, E_1 = E_2 = G_{12} = \nu_{21} = \nu_{12} = 0$</td>
<td></td>
</tr>
<tr>
<td>Fiber compression</td>
<td>$e_f^2 = \left( \frac{\sigma_{11}}{X_c} \right)^2 - 1 &gt; 0, E_1 = \nu_{21} = \nu_{12} = 0$</td>
<td></td>
</tr>
<tr>
<td>MAT54 Chang matrix failure</td>
<td>$e_m^2 = \left( \frac{\sigma_{22}}{Y_T} \right)^2 + \left( \frac{\sigma_{12}}{S_c} \right) - 1 &gt; 0, E_2 = G_{12} = \nu_{21} = \nu_{12} = 0$</td>
<td></td>
</tr>
<tr>
<td>Matrix tensile</td>
<td>$e_d^2 = \frac{(\sigma_{22})^2}{2S_c} + \left[ \frac{(Y_c - Y_T)}{2S_c} \right]^2 - 1 &gt; 0, E_2 = G_{12} = \nu_{21} = \nu_{12} = 0, X_c = 2Y_c$</td>
<td></td>
</tr>
<tr>
<td>Matrix compression</td>
<td>$e_{md}^2 = \frac{(\sigma_{22})^2}{Y_T Y_c} + \frac{(\sigma_{12})^2}{S_c} + \frac{(Y_c - Y_T)\sigma_{22}}{Y_c Y_T} - 1 &gt; 0$</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. MAT54/55 material properties and input values for unidirectional carbon/epoxy

<table>
<thead>
<tr>
<th>Description</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal modulus (GPa)</td>
<td>E11</td>
<td>112.3</td>
</tr>
<tr>
<td>Transverse modulus (GPa)</td>
<td>E22=E33</td>
<td>7.58</td>
</tr>
<tr>
<td>Minor Poisson’s Ratio</td>
<td>v21</td>
<td>0.209</td>
</tr>
<tr>
<td>Shear modulus (GPa)</td>
<td>G12=G23=G31</td>
<td>3.4</td>
</tr>
<tr>
<td>Bulk modulus of failure material (GPa)</td>
<td>K</td>
<td>4.0</td>
</tr>
<tr>
<td>Longitudinal tensile strength (MPa)</td>
<td>XT</td>
<td>2070</td>
</tr>
<tr>
<td>Longitudinal compressive strength (MPa)</td>
<td>XC</td>
<td>1317</td>
</tr>
<tr>
<td>Transverse tensile strength (MPa)</td>
<td>YT</td>
<td>61</td>
</tr>
<tr>
<td>Transverse compressive strength (MPa)</td>
<td>YC</td>
<td>205</td>
</tr>
<tr>
<td>In-plane Shear strength (MPa)</td>
<td>SC</td>
<td>112</td>
</tr>
<tr>
<td>Maximum matrix strain</td>
<td>DFAILM</td>
<td>0.008</td>
</tr>
<tr>
<td>Maximum shear strain</td>
<td>DFAILS</td>
<td>0.032</td>
</tr>
<tr>
<td>Maximum fiber tensile strain</td>
<td>DFAILT</td>
<td>0.0168</td>
</tr>
<tr>
<td>Maximum fiber compressive strain</td>
<td>DFAILC</td>
<td>-0.012</td>
</tr>
</tbody>
</table>
Figure 1. Adjusting SOFT parameters to obtain desired response in LS-DYNA simulations (ref.9).
Figure 2 (a) A user defined contact penetration curve in LS-DYNA. Simulations without (b) and with (c) the contact penetration curve (ref.9).

MAT161/162 (Composite MSC) is a user defined material model available in LS-DYNA with additional license fee. MAT161/162 has been implemented for solid. Based on the principle of Hashin failure criterion, MAT162 has 6 failure modes for laminate and 7 failure modes for fabric composites. The strain rate dependence can also be considered. MAT162 is a damage mechanics based model. The damage evolution law has an exponential form [6]

$$\sigma_i = 1 - e^{m(1-R_j \text{,}^m)}$$

A unique feature of MAT162 is its options for element deletion. An element may erode by three ways: (1) erosion by strain limit as in other models; (2) erosion by compressive relative volume (ratio of current volume to initial volume); and (3) erosion by expansive relative volume. These options provide more rational element deletion. MAT162 appears to be more stable in progressive crash simulations.

1.2 PAM-CRASH

Johnson and Kohlgrüber used a bi-phase model in PAM-CRASH to simulate the crash behavior of composite components for helicopters [11]. The bi-phase model appears to be a damage mechanics model implemented for shell. Its compliance matrix is given as

$$[S] = \begin{bmatrix}
\frac{1}{(1-d_1)E_1} & -\frac{v_{12}}{E_1} & 0 \\
-\frac{v_{12}}{E_1} & \frac{1}{(1-d_2)E_2} & 0 \\
0 & 0 & \frac{1}{(1-d_{12})G_{12}}
\end{bmatrix}$$

Figure 3 depicted the damage evolution law and the resulted stress-strain curve. Figure 4 presents a comparison of simulations with experiment.
Figure 3 PAM-CRASH bi-phase model. The damage evolution law and the resulted stress-strain curve.

Figure 4 Simulations using PAM-CRASH bi-phase model and experimental results [11].

Johnson et al have implemented Ladeveze’s composite damage mechanics model in PAM-CRASH for shell [12] and incorporated cohesive interfaces to simulate delamination [13]. Figure 5. The damage-plasticity model together with delamination modeling appeared to be inadequate to model the axial crash cases in CMH-17 numerical round robin. To improve the correlation, different triggers were used for composite components of different shapes [13], as shown in Figure 6.
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Figure 5 Mesoscale modeling of delamination for crash simulation (Johnson, 2011).

Figure 6. Different triggers were used in the chamfer area in order to correlate with experimental results (Johnson, 2011).

1.3 RADIOSS

The composite model that has been reported in crash simulations is COMPSH (25) [14,15]. Unlike any other composite models, COMPSH is based on an anisotropic plasticity framework with Tsai-Wu criterion to define yield and work hardening, Figure 7. The model also employs a set of linear damage laws to describe the softening response above the failure strain. It may model either elastic failure or plastic failure, as shown in Figure 8. COMPSH is available for both shell and solid. RADIOSS simulations tend to be more stable than those using other codes.
1.4 ABAQUS

ABAQUS Explicit has been used in crash simulations of composite components. Composite material models are often in the form of VUMAT, user material model for explicit ABAQUS. Examples are the micromechanics model for braided composites developed by Stanford (solid) [16,17], and ABAQUS internal VUMAT for fabric reinforced composites (shell) [18]. Often these models are proprietary.
CZone [18], developed by Engenuity for crash simulations, is worth mentioning. CZone is an add-on product with ABAQUS. Similar to the contact penetration in LS-DYNA, CZone is defined at where a structure makes contact with rigid bodies or stiff structures. CZone allows an element to pass through the contact zone with a constant crush stress before being eliminated from the model, as illustrated in Figure 9. The crush stress is measurable using a special crush test rig, as shown in Figure 10. CZone is very stable such that the crash response of a structure of constant cross-section becomes a straight line, as shown in Figure 11.

Figure 9. CZone approach - element passes through the contact zone with a constant crush stress before being eliminated from the model (ref.18).

Figure 10. The testing rig for CZone crash force calibration and some typical results (Ref.18).
In summary, crash simulations of composite components have been attempted with both progressive failure models and damage mechanics based models. The recent development appears to favor damage mechanics based models.

Constitutive models alone are not sufficient to model the progressive crash of composite components. The element type is also important. The solid element representation allows a volume of material being crashed as in reality but it is computational expensive. Shell elements are highly efficient in representing the in-plane stretching and out-of-plane deformation but they are inadequate under large in-plane compressive deformation. With shell, it is difficult to capture the progressive failure behavior, particularly at the beginning of the crash. This presents a unique challenge in composite component crash simulations. To simulate the progressive crash, different triggering or softening mechanisms have been developed, such as the CZone, contact penetration, SOFT parameter, and various ways to model the chamfer, etc. These interventions are needed for the sake of simulations but some of them may not represent the real physics.
2. Task 13.2 Select progressive crash models from public domain

Ladevèze model, also called Cachan model has been selected.

Cachan model, developed by the research group of Ladevèze at LMT Cachan, France [19-28], is one of the most widely used approaches of continuum damage mechanics models for fiber reinforced composites based on energy potentials. They introduced the concept of meso-model, which contains two constituents: single-ply and the interface. Single plies are used to represent intralaminar failure mechanisms (MDF and FF), while two-dimensional interfaces are used to transmit tractions from one layer to the next, for the modeling of delamination. The state of damage is uniform within each meso-constituent. [21, 29] Cachan model has been adopted by several other authors [12, 30-33] and shows good agreement with experimental results.

Cachan model takes into account stiffness recovery and inelastic strains [29]. As shown by Xiao [35], material models that do not take into account the plastic features of composites failures might underestimate the energy absorption capacity of composite structures. Cachan model is sufficient to describe the nonlinear or plastic behaviour that some thermoset or thermoplastic composites might exhibit, especially under transverse and shear loading [30].

Unlike some other models that are only able to provide valuable insight into some particular forms of damage, Cachan model are not limited to a specific loading and configuration. Phillips et al. [31] demonstrated that Cachan model was able to predict damage regardless of fiber orientations.

From a practical point of view, the difficulty of most damage models is to characterize a great number of parameters needed to describe the damage behavior. All the parameters needed in the elementary ply of a Cachan model can be measured by experiment as listed in ref [20]. Johnson et al [14,15,32] used Cachan model to model the impact and crash behavior of fabric reinforced composites and showed that the delamination modeling strategy works well.

Cachan model has been developed for more than 20 years. In some later work, it is extended to consider additional phenomena, like damage in fiber direction in the same fashion as in other directions, the influence of ply damage variables on out-of-plane moduli E3, G13, and G23 [22,23] and damage-delay in moderately dynamic analyses [28]. In order to get a better understanding and prediction of fracture, the modified Cachan model is even able to connect the micromechanics and mesomechanics of laminate composites [23].
3. References

13. Johnson AF, CMH-17 Crashworthiness WG Round Robin Simulation of Crash Elements, CMH-17 58th Meeting, November 14-17, 2011, Wichita, KS.
34. Xiao X. Modeling energy absorption with a damage mechanics based composite material model. Journal of Composite Materials, Vol. 43, No. 05/2009