New constitutive model for woven thermoplastic composite materials.

Authors: Pieter Volgers[1], H. Kuhlmann[2], Z. Zhang[2]

[1] DuPont Performance Polymers, European Technical Center, Geneva, Switzerland
[2] DuPont Engineering Technologies, Chestnut Run Plaza, Wilmington, Delaware, U.S.A

Abstract: *This paper describes the behavior of the DuPont thermoplastic composite sheet offering, under the name DuPont™ Vizilon™ and matches this to composite models as implemented in Abaqus. Subsequently, to obtain a more accurate description of the actual behavior of these materials, DuPont has developed a new material model by combining both plastic deformation of the thermoplastic matrix material with a more classical composite damage model for the description of the non-linear permanent deformation of the woven continuous fiber reinforcement and subsequent failure. The (current) results obtained with this model, implemented in Abaqus, are presented, demonstrating the potential of this model for thermoplastic composites.*

Keywords*: Composites, Constitutive Model, Crashworthiness, Damage, Fabrics, Failure, Plasticity, Polymer.*

1. Introduction

In order to meet the ever more stringent requirements on fuel consumption and CO2 emissions, the automotive industry pursues various solutions, of which the reduction of mass is an important aspect, which creates a snow-ball effect to emission reduction, such as further engine downsizing. Thermoplastic composites (TPCs) are being developed to compete with metals for the use in structural design and light-weighting. To that goal, the end-customer needs to be able to accurately predict its performance to a level comparable to that of the non-in-kind competition. As part of its offering, DuPont has been improving the state-of-the-art of thermoplastic composite analysis for its Vizilon™ thermoplastic composite materials with the models available in various software packages.

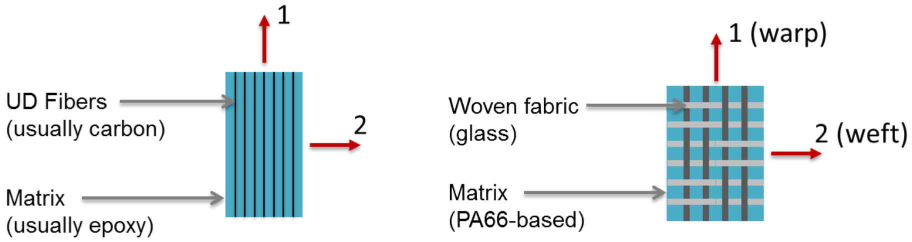

Figure 1: 'Classical' UD composite vs Vizilon™ TPC

Vizilon™ thermoplastic composite differentiates itself from a ‘classical’ fiber-reinforced composite material, such as a carbon-fiber epoxy as found in many applications in a few distinct areas, as shown in Figure 1. Whereas a ‘classical’ composite uses uni-directional fibers set in a thermoset matrix, such as epoxy, on a layer-by-layer basis, Vizilon™ thermoplastic composite is based on a woven fabric fully impregnated and consolidated in a thermoplastic polymer (such as a polyamide) as a sheet of multiple layers, which each layer placed in the same direction. This is the result of the continuous manufacturing process to produce the sheet, non unlike the rolling of sheet metal plates. As a result, where a ‘classical’ UD composite layer has a main direction with significantly more dominant properties in the fiber direction than the properties perpendicular to the fibers (denoted as the 1- and 2-direction, respectively), the woven sheet has two main directions with identical or similar properties and behavior. In addition to that, the thermoplastic polymer matrix made of Vizilon™ product shows a much more ductile behavior than a much stiffer and more brittle thermoset matrix. As will be shown in this paper, these differences are fundamental when trying to provide a mathematical description of the material behavior.

An extensive material testing program allowed the full characterization of the material behavior, the selection of suitable material models and their corresponding material model parameters. This paper describes the material testing program and the evaluation of different material models available in Abaqus. Based on a study of the theoretical models in Abaqus and their corresponding performance in the correlation to the actual material behavior, DuPont implemented an updated material model to more accurately describe the actual observed material behavior.

2. Material testing program

The first step for the modeling of any material is the generation of material property data through standard material tests. For a continuous fiber reinforced composite, it is natural to assume that the material behavior is anisotropic. As the thermoplastic composite sheet is made from woven fabric, whereby all the layers are oriented in the same direction, as a first approximation we assume the material behavior to be globally orthotropic, despite the multiple layers, with the warp and weft directions corresponding to the principal orthotropic axes. The assumption of material orthotropy reduces the linear elastic in-plane material parameters to 2 elastic moduli, one shear modulus and one Poisson ratio. For reasons of simplicity, the out-of-plane properties will not be considered in this paper. Basic material testing then consists of measuring the behavior of the tensile and compressive behavior in the main orthotropic (fiber) directions and the shear. The off-axis tensile properties should then follow automatically and can be used to verify the material model.

Following initial material characterization and evaluation, a second round of material testing was added to further understand the material behavior with the objective of more accurately predicting the performance of structural parts, particularly under complex and/or crash loading.

DuPont's Vizilon™ offering consists of different types of materials. In this paper we will concentrate on one single grade, Vizilon™ SB63G1, a balanced, 2/2 twill glass fabric with 63% (mass) fiber content, with a PA66-based matrix resin, which corresponds to a 44% fiber volume fraction (to remain consistent with traditional short fiber polymer nomenclature DuPont refers to the fiber content in terms of mass). The balanced weave allows us to assume that the properties in the warp and weft direction are (in theory) identical. Mechanical testing has shown a slight difference in performance between the two directions, but this is sufficiently small to be neglected for the purpose of this paper when determining the corresponding material model parameters.

For legal and confidentiality reasons, the stresses are presented on a relative scale, whereby the failure stress in the main (warp) direction at room temperature is taken as 100%.

2.1 Testing conditions

Standard material testing of tension and compression in the main fiber direction has been performed following ISO standards for composite testing (ISO 527-4, 199; ASTM D7078, 2005). With the matrix material being a thermoplastic polymer, a certain dependency on the temperature is to be expected. Hence, material tests have been performed at a range of temperatures from -40 °C to +120 °C. This allows us to get a good indication of the relative influence of the matrix material, the mechanical properties of the glass fibers not being subject to change in this temperature range. As the polymer is PA66-based, the behavior is also dependent on the moisture content. Following traditional practice of the polymer resin business, the material tested has been conditioned to moisture content corresponding to the equilibrium found at 50% relative humidity (RH) at 23°C. The specimen testing sample schematic is shown in Figure 2.

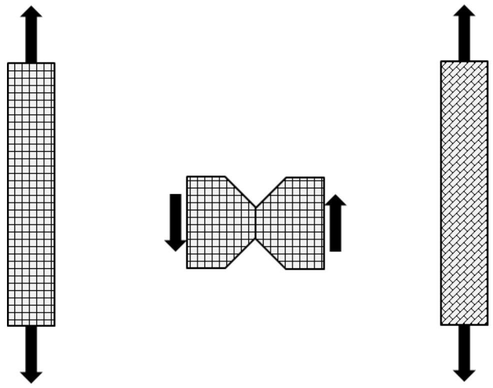

Figure 2: Schematic of tensile testing in the warp/weft direction, shear and 45-degree biased tensile

2.2 Tensile and compression in main fiber direction

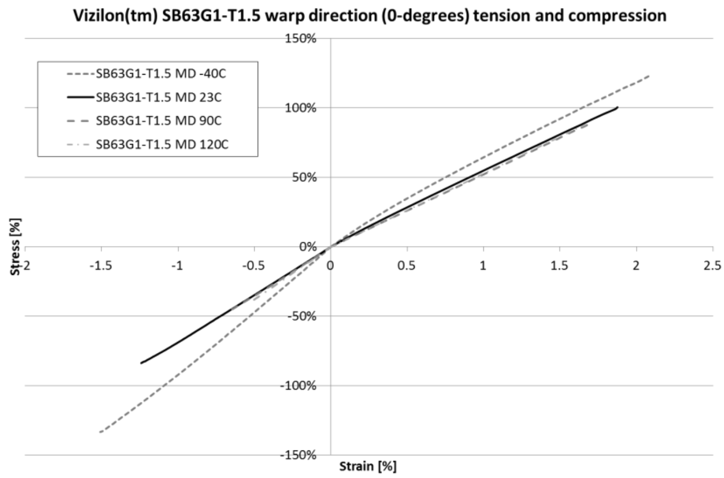

Figure 3: Tensile and compressive stress-strain curves in warp direction

Figure 3 shows the tensile and compressive stress-strain curves for the composite material in the warp (main fiber) direction. As the material considered uses a symmetric weave for the continuous fiber reinforcement, the properties in the waft direction are very similar. We notice an almost identical modulus in both tension and compression in the temperature range from 23°C to 120°C, but with a reduced failure stress with increasing temperature. The property change at -40°C is more pronounced, as this takes the polymer matrix below the glass-transition temperature (Tg). Furthermore, the compressive failure strength is well below the tensile strength. A closer study of the test specimen shows that, while failure in tension is abrupt, in compression the sample maintains a limited cohesion, allowing a continued (but strongly reduced) structural resistance which allows for the continued absorption of energy. This behavior is well known for composites, but is much more pronounced when using a woven fabric and a thermoplastic polymer matrix. However, this behavior is hard to measure using traditional equipment, as the standard programming of a MTS machine stops the equipment and the recording when a strong abrupt reduction of resistance is reached.

2.3 Shear testing

The shear testing uses a V-notched Iosipescu sample and set-up (ASTM D3410, 2008) which provides a direct measurement of the shear properties. Aramis digital image measurements are used instead of strain gauges as described in the norms to better interpret the test data and avoid the averaging of the strain in the zone of the gauge. This is all the more important given the large strain gradient observed in the center of the sample where the shear deformation is measured.

Contrary to tensile testing in the main fiber direction, a small linear elastic region is soon transformed into a large non-linear plastic zone with failure strains up to 50%. At this point the woven fabric is severely deformed and fibers oriented towards the direction of the loading. Also, a strong dependency on the temperature is observed. This shows that the shear properties are heavily dependent on the performance of the matrix material. Tests on sheets with higher glass content show a lower shear performance, demonstrating that the shear behavior comes almost completely from the matrix material.

2.4 45-degree off-axis tensile loading

To verify the orthotropic behavior and the shear properties, particularly the shear modulus, tensile tests at specimens cut at 45 degree angle have been performed. Results are shown in Figure 4. One immediately notices that the stress-strain curves resemble much closer the shear data than the tensile testing in fiber direction, which a significant plastic region. While the failure stress is significantly lower when tested in the 45-degree direction compared to the main fiber directions, the failure strain is much larger.

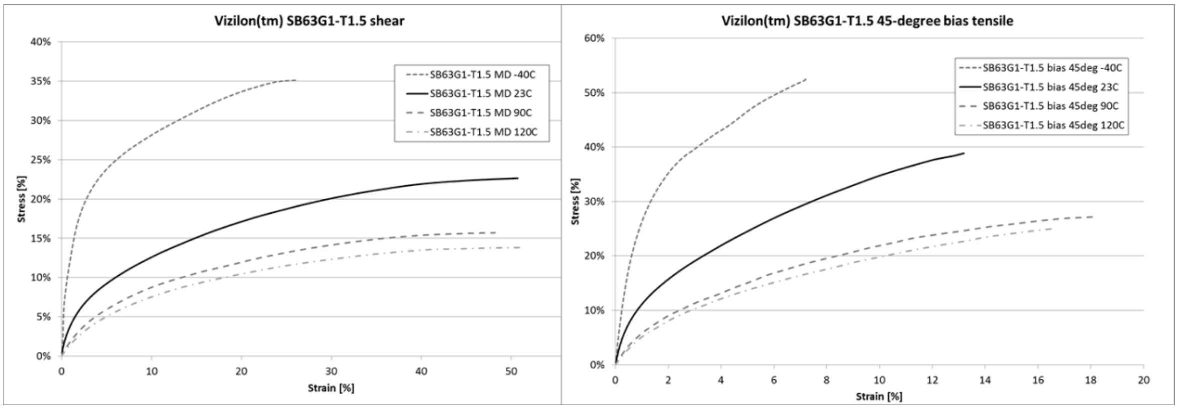

Figure 4: Shear and 45-degree off-axis tensile testing

3. Evaluation of existing material models

The ultimate objective for the material modeling by DuPont is to provide customers with the necessary know-how and capabilities to analyze and design structural components using the Vizilon™ thermoplastic composite sheet offering. It was therefore decided to concentrate the development effort towards existing material models. Abaqus is the global standard in DuPont for structural analysis and has excellent material model capabilities and the possibility to change from static implicit to dynamic explicit analysis within the same environment using the same material model. A study in the various orthotropic material models available in Abaqus was done to evaluate their performance.

To evaluate the behavior and performance of the various material models considered, the tensile test in warp direction, the V-notched shear test and the tensile test at 45-degree bias were simulated and the resulting nominal stress-strain curves compared.

3.1 Linear orthotropic model with classical failure criteria

As a first step, a linear orthotropic material model was used excluding any permanent deformation due to plasticity or damage. Providing the failure stress and strain in the different orthotropic directions allows the post-processor to evaluate the different classical failure criteria (Abaqus, Section 22.2.3), such as maximum stress, maximum strain, Tsai-Hill or Tsai-Wu. The material is assumed broken when the failure criterion is larger than 1.

The maximum stress or –strain criterion simply considers the stress or strain in the main orthotropic directions and shear, with possible different values for tension and compression.

$$X = \sigma_{tension}^{fail} if\ \sigma > 0, otherwise\ X = \sigma_{compression}^{fail}$$

$$X = \sigma_{11}^{fail}; Y = \sigma_{22}^{fail}; S = \sigma_{12}^{fail}$$

$$\mathrm{FC_{max}} = max\left(\frac{\sigma_{11}}{X}, \frac{\sigma\_22}{Y}, \left|\frac{\sigma_{12}}{S}\right|\right)$$

For the maximum strain criterion replace the stresses by the strains.

The Tsai-Hill criterion provides an orthotropic failure measure similar to Hill's orthotropic yield criterion for plasticity and is given by:

$$FC_{TsH} = \frac{\sigma_{11}^2}{X^2} - \frac{\sigma_{11}\sigma_{22}}{X^2} + \frac{\sigma_{22}^2}{Y^2} + \frac{\sigma_{12}^2}{S^2}$$

The material specimen test set-ups were modelled and simulated. Obtained reaction forces and displacements between the extensometer grips are converted into nominal stress and strain and compared to the average stress-strain curves obtained from testing. (We will use the stress as a comparative measure and not the reaction force to eliminate the measured differences in thickness.) Figure 5 shows the resulting curves from the test data (continuous lines) and the simulated test (dashed lines) for the 0- and 45-degree tensile test as well as the shear test.

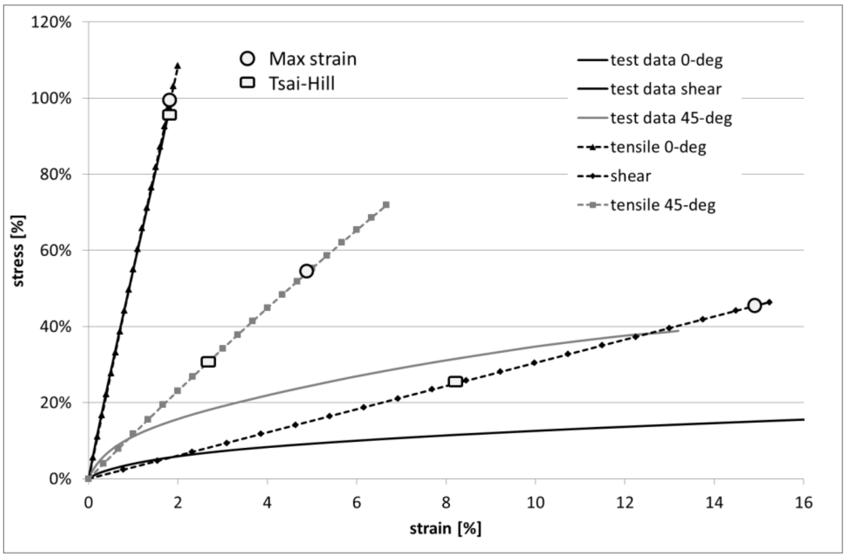

Figure 5: Predicted failure using different criteria for 3 test conditions

Using the different failure criteria available, we can determine their predicted failure point for the different test conditions. For the material data available, the Tsai-Hill and Tsai-Wu gave very similar results, and hence only the former will be shown here. As expected, the failure of the material in the main fiber direction is predicted properly using all conditions. The problem occurs for the off-axis and shear tests, where the orthotropic material model predicts a linear response while the test data shows a large non-linear region. For the calculated stress-strain response not to deviate too much from the measured data beyond the elastic region, the initial shear modulus was reduced by 50%. The maximum strain criterion is the best to predict the maximum allowable deformation, but even this criterion strongly under-predicts the deformation capabilities of the material in off-axis testing. The Tsai-Hill criterion predicts the maximum stresses in both off-axis and shear remarkably well, but is also hampered by the linear response of the orthotropic elastic model.

3.2 Orthotropic elastic model with Hashin-type damage

In order to account for the non-linear response of a continuous fiber composite material, a Hashin-type damage model is available in Abaqus (Abaqus, Section 24.3). The theory developed by Hashin (Hashin, 1980, Hashin and Rotem, 1973) forms the basis for most composite damage models found in the various commercial finite element codes.

The damage model consists of two components: the damage initiation criteria to determine the start of the damage, and the damage evolution equations. The model is clearly developed for uni-directional fiber reinforced layers, as described in the beginning of this paper. Damage initiation is based on 4 criteria:

- Fiber tension failure $F_f^t = \left(\frac{\hat{\sigma}_{11}}{X_t}\right)^2 + \alpha\left(\frac{\hat{\tau}_{12}}{S_l}\right)^2$
- Fiber compression failure $F_f^c = \left(\frac{\hat{\sigma}_{11}}{X_c}\right)^2$
- Matrix tension $F_m^t = \left(\frac{\hat{\sigma}_{22}}{Y_t}\right)^2 + \left(\frac{\hat{\tau}_{12}}{S_l}\right)^2$
- Matrix compression $F_m^c = \left(\frac{\hat{\sigma}_{22}}{2S_t}\right)^2 + \left[\left(\frac{Y_c}{2S_t}\right)^2 - 1\right] \cdot \frac{\hat{\sigma}_{22}}{Y_c} + \left(\frac{\hat{\tau}_{12}}{S_l}\right)^2$

Where X_t, X_c, Y_t, Y_c tensile and compressive strength in longitudinal and transverse direction, respectively, as before, and S_l and S_t the longitudinal and transverse shear stress, and ^ indicates equivalent stress.

One immediately notices the very different expressions for the compression failure in the fiber and matrix direction. While for a ‘classical’ UD composite layer the failure in the main fiber direction is determined by the performance of the fiber, and the failure perpendicular to this is determined by the properties of the matrix material, this assumption is not valid for a woven thermoplastic composite, and determining material parameters which fit the observed behavior is therefore complicated.

The damage evolution has been implemented by reducing the stress according to:

$$\hat{\sigma} = \begin{bmatrix} \frac{1}{1-d_f} & 0 & 0 \\ 0 & \frac{1}{1-d_m} & 0 \\ 0 & 0 & \frac{1}{1-d_s} \end{bmatrix} \cdot \sigma$$

With the following evolution relations:

- Fiber tension ($\hat{\sigma}_{11} \geq 0$) $\delta_{eq}^{ft} = C\sqrt{\langle\epsilon_{11}\rangle^2 + \alpha\epsilon_{12}^2}$
- Fiber compression ($\hat{\sigma}_{11} < 0$) $\delta_{eq}^{fc} = C\langle\epsilon_{11}\rangle$
- Matrix tension ($\hat{\sigma}_{22} \geq 0$) $\delta_{eq}^{mt} = C\sqrt{\langle\epsilon_{22}\rangle^2 + \epsilon_{12}^2}$

- Matrix compression ($\hat{\sigma}_{22} < 0$) $\delta_{eq}^{mc} = C\sqrt{\langle -\epsilon_{22}\rangle^2 + \epsilon_{12}^2}$

The damage evolution for each mode is then given by:

$$d = \frac{\delta_{eq}^{fail}(\delta_{eq} - \delta^0)}{\delta_{eq}(\delta^{fail} - \delta^0)};\; d_s = 1 - (1 - d_t^t)(1 - d_f^c)(1 - d_m^t)(1 - d_m^c)$$

Notice that the basic Hashin damage does not include an independent evolution of the shear damage.

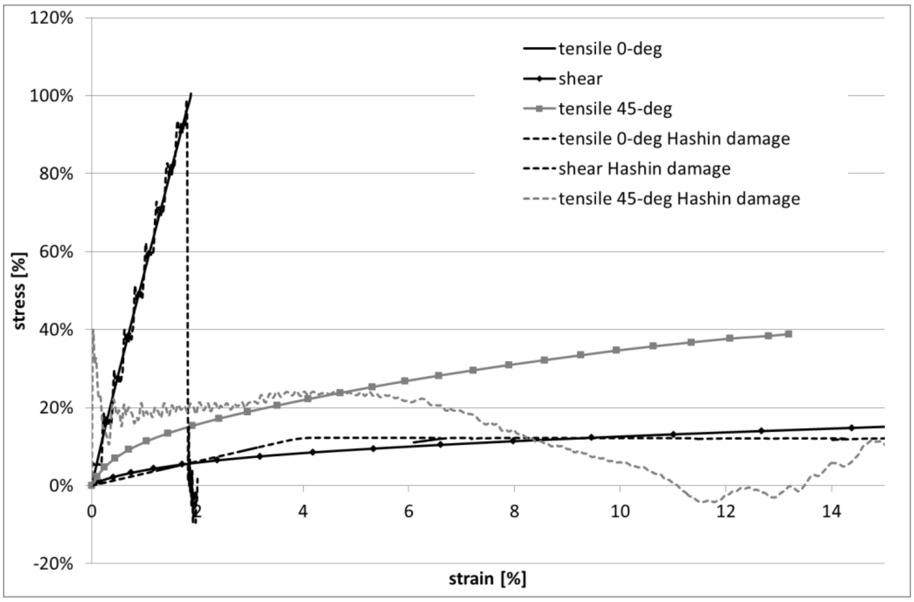

Figure 6: Predicted failure behavior using Hashin-type damage

The numerical results after longtime optimizing the material damage parameters are shown in Figure 6. As one would expect, the tensile behavior in the main fiber direction is reproduced properly. Having adapted the material model parameters to the best of our capabilities, the shear behavior could be matched to a satisfactory level, but the behavior in the weft (perpendicular to the main fiber, or warp, direction – not shown) and the off-axis direction is far from satisfactory. The initial response of the model of the 45-degree off-axis tension test is too stiff, in order to approach the curve until about 4% strain, after which the stiffness softens and generates a downward curve not representative of reality.

The conclusion has to be that the material model does not describe the actual physical behavior. However, for components which are principally loaded in the main fiber direction and with possibly a significant shear contribution (such as a general beam under 3-point loading) the model can reasonably predict the structural performance. But for structures loaded off-axis to the warp direction, results do not correspond to observed physical behavior.

3.3 Orthotropic elastic-plastic model with Hill's yield criterion

Given the large plastic deformation in the off-axis tensile and shear test, the use of an elastic-plastic model should be considered. Abaqus allows this to be combined with an orthotropic elastic model and an anisotropic yield criterion for the plastic deformation according to Hill (Hill, 1979):

$$f(\sigma) = \sqrt{F(\sigma_{22} - \sigma_{33})^2 + G(\sigma_{33} - \sigma_{11})^2 + H(\sigma_{11} - \sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2}$$

Where F, G, H, L, M and N are constants (Abaqus, Section 23.2.6) related to the yield stress ratios R_{ij}.

The plastic response is provided in terms of a true-stress vs plastic strain curve based on the shear test data and the yield stress ratios are calculated accordingly. We assume an isotropic plastic flow function.

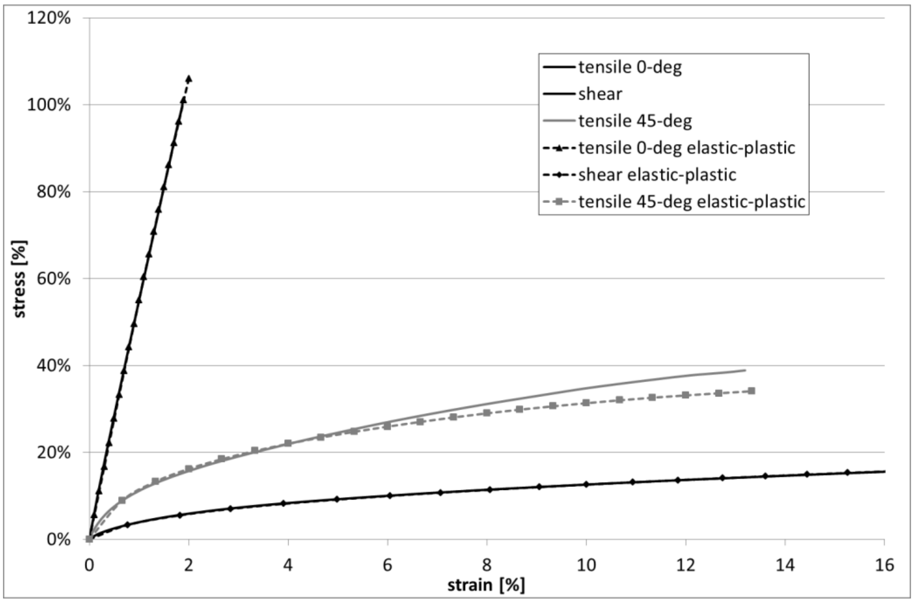

Figure 7: Predicted behavior (without failure) using elastic-plastic model

Simulating the three standard coupon tests as before, we obtain the response curves as shown in Figure 7. A perfect match is found for the 0-degree tensile test as well as the shear test, although the material will continue to deform due to the absence of any failure mechanism in the model. But also the 45-degree bias tensile test provides an accurate result, with the measured response being slightly stiffer after about 6% strain. This effect is due to the fact that the woven fabric fibers start to shear whereby the fibers are being oriented in the direction of the load, increasing the effective stiffness. The material model itself maintains its assumption of orthotropy of the woven fabric.

4. Development of new material model

Looking at the simulation results obtained with the different material models as described above, we can conclude that classical anisotropic Hill plasticity allows for an accurate description of the shear deformation, including off-axis tension loading, while the Hashin damage modelling can predict the loss of stiffness and failure in the fiber direction.

An improved material model which accurately describes the material behavior as observed in the material tests above should therefore consist of:

- A general plasticity model whereby the main plastic deformation occurs through shearing of the matrix material;
- A (Hashin-type) damage model superimposed on top of this plasticity model to account for loss of stiffness and failure;
- A damage model with identical damage mechanism (but not parameter values) for both orthotropic fiber directions (warp and weft);
- An independent damage factor and failure mechanism for shear.

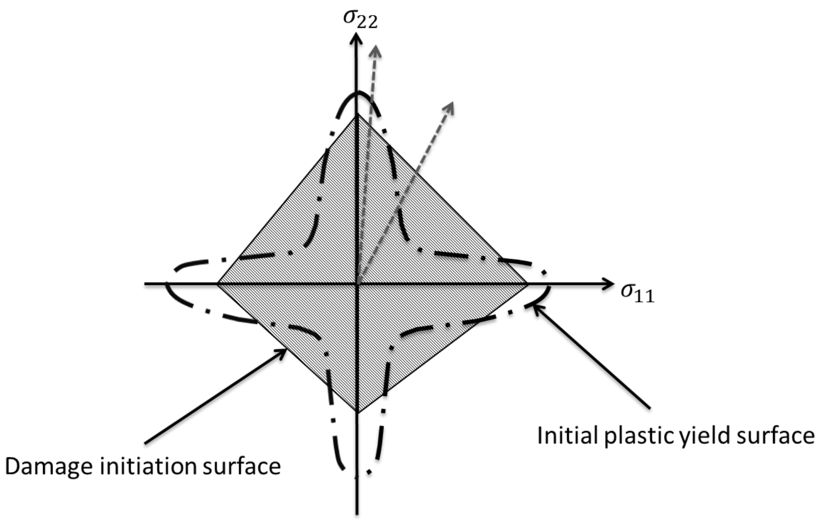

Figure 8: Proposed superposition of plastic and damage initiation

A schematic of the mapping of plasticity and damage is shown in Figure 8. The red/dash-dot line indicates the initial plastic yield surface similar to the yield function used in this paper. The yellow/shaded region shows the potential damage initiation surface, which partially overlaps. For loading in the main fiber directions the stress-state will reach the damage initiation surface first, causing the material to rupture or fail before the potential plastic yield surface has been reached. For stronger off-axis loading, the plastic yield will be reached first. Pure elastic-plastic deformation will occur, expanding the yield surface, until the damage initiation surface is reached. At that point, both permanent deformations will occur simultaneously until total failure has been reached.

This principal should be relatively easy to implement in Abaqus starting from the existing elastic-plastic material model. This differs from the Johnson-Pickett material model for woven fabrics (Johnson et.al., 2001) as implemented in PAM-Crash, which only considers plasticity for the shear deformation in the constitutive equations. The resulting model creates not only complex equations, but also requires non-physical material model parameters for calibration.

4.1 Theory and implementation

A macro mechanical approach was used to predict damage progression and failure. This approach represents the damage onset and damage progression whose properties are degraded prior to ultimate failure. A continuum damage mechanics formulation is used following the work by Pinho (Pinho et.al., 2006) in which material degradation parameters are internal state variables which are governed by damage evolution equations. It is computationally more efficient, especially for simulating damage in a large scale structure.

4.1.1 Damage initiation

Damage initiation refers to the onset of degradation at a material point. Once damage initiation occurs, the material starts to be degraded. Damage initiation is defined as follows (t indicating tension, c indicating compression):

$$OD_1{}^{t,c} = \sqrt{\left(\frac{\hat{\sigma}_{11}}{X_{t,c}}\right)^2}$$

$$OD_2{}^{t,c} = \sqrt{\left(\frac{\hat{\sigma}_{22}}{Y_{t,c}}\right)^2}$$

Onset of fiber damage takes place when ${OD_i}^{t,c} = 1\,; i = 1{,}2$. Onset of shear damage takes place when $OD_{12} > 1$ and is defined as:

$$OD_{12} = \left\{ \quad max\{\sqrt{\left(\frac{\hat{\sigma}_{11}}{AS_1}\right)^2 + \left(\frac{\hat{\sigma}_{12}}{S_{12}}\right)^2}, \sqrt{\left(\frac{\hat{\sigma}_{22}}{AS_2}\right)^2 + \left(\frac{\hat{\sigma}_{12}}{S_{12}}\right)^2}\} \right.$$

Where

$$if\ \sigma_{11} > 0 \qquad AS_1 = X_t$$
$$if\ \sigma_{11} < 0 \qquad AS_1 = X_c$$
$$if\ \sigma_{22} > 0 \qquad AS_2 = Y_t$$
$$if\ \sigma_{22} < 0 \qquad AS_2 = Y_c$$

4.1.2 Damage Evolution

The damage evolution is implemented by reducing the stress as described in (Abaqus, Section 24.3). The compliance matrix has three scalar damage parameters df, dm, ds, which have values 0 ≤ di ≤1 and represent modulus reductions under different loading conditions due to damage in the material. For laminate plies, df and dm are associated with damage and failure in the principal fiber directions, and ds with in-plane shear failure.

The damage evolution is based on an equivalent displacement and stress for each of the damage modes that are defined as follows:

- Tension in principal direction 1 when ${OD_1}^t = 1$ $\qquad dfteq_1 = L^c * ef_t$
- Compression in principal direction 1 when ${OD_1}^c = 1$ $\qquad dfceq_1 = L^c * ef_c$
- Tension in principal direction 2 when ${OD_2}^t = 1$ $\qquad dfteq_2 = L^c * ef_t$
- Compression in principal direction 2 when ${OD_2}^c = 1$ $\qquad dfceq_2 = L^c * ef_c$
- Tension in principal directions and shear when $OD_{12} = 1$ $\qquad dfteq_{12} = L^c\sqrt{{ef_t}^2 + {ef_s}^2}$
- Compression in principal directions and shear when $OD_{12} = 1$ $\qquad dfceq_{12} = L^c\sqrt{{ef_c}^2 + {ef_s}^2}$

The damage evolution is based on an equivalent displacement and stress for each of the damage modes that are defined in a similar manner as the Hashin-type damage as described in the previous section, but with an independent damage variable for shear:

$$d_s = 1 - (1 - d_{s1})(1 - d_{s2})$$

Where d_{s1}, d_{s2} are defined as above, and:

$$d = \frac{(\delta_{eq} - \delta_{eq}^{OD})}{(\delta_{eq}^{f} - \delta_{eq}^{OD})}$$

Where δ_{eq}^{OD} is the equivalent displacement at the onset of damage, δ_{eq}^{f} is the equivalent displacement at which the material is completely damage and δ_{eq}, which is always $\delta_{eq}^{f} \geq \delta_{eq} \geq \delta_{eq}^{OD}$, is the equivalent displacement at time i. The characteristic length L^c is based on the element geometry and formulation. For a shell it is a characteristic length in the reference surface, computed as the square root of the area.

4.1.3 Implementation in Abaqus

The damage and failure modelling has been implemented in Abaqus through the use of user-defined fields (`UFIELD`) and user dependent state variables (`DEPVAR`). This method was preferred over the writing of a separate independent user-defined material model to allow the use of the existing material model in Abaqus/Explicit and only modify the behavior in the damage and failure domain.

The 4 state variables are related to the damage variables and allow Abaqus/Explicit to determine the effective stiffness of the material. These state variables are calculated in a user subroutine `VUSDFLD` implemented in Abaqus/Explicit. This routine takes the 8 user defined fields as input, which determine the failure stress in warp direction in tension and compression, the failure stress in weft direction in tension and compression, failure strain in tension and compression, the damage initiation stress in shear and a controlling parameter, respectively. Current implementation does not include strain-rate dependency for the failure stress, but different values can be specified depending on the actual strain-rate in the model to obtain a more accurate prediction for dynamic loading.

The nonlinear material behavior of a composite laminate can be specified as a function of solution-dependent variables. The user subroutine `VUSDFLD` in Abaqus/Explicit was used to modify the behavior of the nonlinear material and to include the effects of damage. The material model presented in this paper, includes damage, and various modes of failure. After onset of damage, the stress-carrying capacity degrades gradually with increasing strain. The values of the failure indices are not assigned directly to the field variables: instead, they are stored as solution-dependent state variables.

The user defined variables are defined for the input of the elastic engineering constants. In addition to this, the plasticity definition as used in the elastic-plastic model described above is added. This method allows for the inclusion of strain-rate dependency for the plastic behavior.

4.2 Evaluation of initial performance

Evaluation of the performance and potential of the material model is done through the specimen tests as before and results are shown in Figure 9. This shows the capabilities of the newly implemented material model.

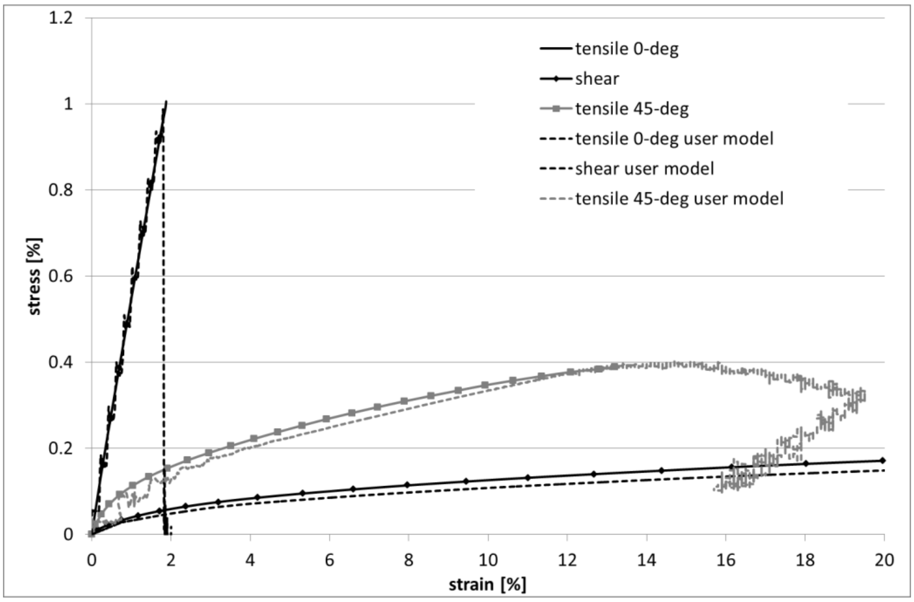

Figure 9: Predicted behavior with new material model

The damage parameters were systematically obtained by correlating simulations with standard quasi-static and high-rate tensile coupon, compression and shear test. The parameters are adjusted over several simulation runs until satisfactory correlation is obtained. The linear behavior of the tensile test in main fiber direction is preserved, but now allows failure to occur. The 45-degree bias tensile response follows both the elastic and the non-linear part of the curve until failure occurs, after which the material is damaged and fails.

The material model was then further validated and refined with simulations on dynamic impact plaque tests and three-point bending tests, which induce more complex loading conditions.

5. Summary and Conclusions

This paper describes the theoretical aspects of material models available in Abaqus applied to the Vizilon™ offering, a composite sheet based on woven continuous fiber reinforcements and a thermoplastic polymer matrix. The material is characterized for these models and their performance evaluated by simulating the standard material tests of traction in the main fiber direction, V-notched shear and traction at 45-degrees angle to the main fiber direction, of which the results are summarized in Figure 10. A symmetric (balanced) woven fabric was used to eliminate the additional effort of different material parameters in warp and weft direction.

It has been shown that advanced material modeling for composite materials is currently aimed principally at high-performance use of these materials, which use a uni-directional (UD) fiber placement per layer with a thermoset matrix. Simulation results with the aim to reproduce the behavior of a woven thermoplastic composite sheet demonstrate that these models do not address the specific characteristics of such a material, principally:

- Similar damage and failure mechanism in both axes of orthotropy (fiber warp and weft direction);
- Large plastic deformation in shear and in off-axis loading.

Further literature study revealed that very little work has been done on the modelling of woven thermoplastic composite materials. This motivated DuPont to develop and implement a new material model in Abaqus by superimposing a damage and failure model on top of an elastic-plastic model using Hill's anisotropic yield criterion. This approach should (theoretically) have the advantage of a methodology approaching micro-mechanical modelling and allow for a simple implementation and determination of the corresponding material parameters.

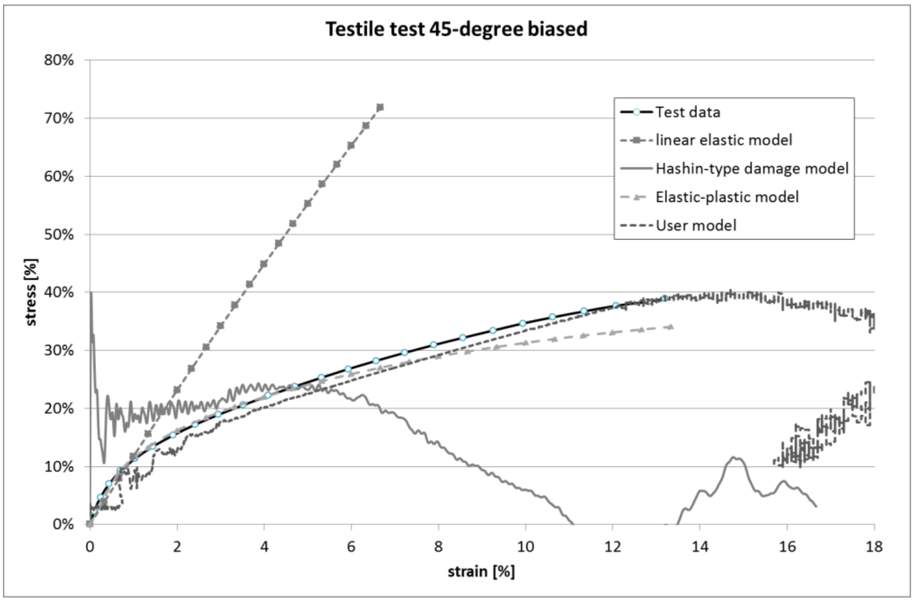

Figure 10: Summary numerical analysis results for 45-degree off-axis tensile test

The material model implemented by DuPont in Abaqus has been described and initial results presented. This paper shows the promising performance of this material model for describing more accurately the behavior of a thermoplastic composite woven sheet.

6. References

1. Abaqus Analysis User's Guide, Version 6.14, Dassault Systèmes Simulia Corp., Providence, RI.
2. ASTM D7078/7078M-05, ASTM International, West Conhohocken, PA, USA, 2005
3. ASTM D3410/3410M-03, ASTM International, West Conhohocken, PA, USA, 2008
4. Hashin, Z., "Failure Criteria for Unidirectional Fiber Composites," Journal of Applied Mechanics, vol. 47, pp. 329–334, 1980.
5. Hashin, Z., and A. Rotem, "A Fatigue Criterion for Fiber-Reinforced Materials," Journal of Composite Materials, vol. 7, pp. 448–464, 1973.
6. Hill, R., "Theoretical plasticity of textured aggregates," Mathematical Proceedings of the Cambridge Philosophical Society, 85(1), pp 179–191, 1979
7. ISO 527-4, International Organization for Standardization, Geneva, Switzerland, 1997
8. Johnson, A.K., Pickett, A.K., and Rozycki, P., "Computational methods for predicting impact damage in composite structures," Composite Science and Technology, Vol 61 (15), pp 2183-2192, 2001.
9. Pinho, S.T., Iannucci, L., and Robinson, P., "Physically-based failure models and criteria for laminated fibre-reinforced composites with emphasis on fibre kinking: Part I: Development," Composites Part A: Applied Science and Manufacturing, Vol. 37 (1), pp 63-73, 2006.
10. Pinho, S.T., Iannucci, L., and Robinson, P., "Physically-based failure models and criteria for laminated fibre-reinforced composites with emphasis on fibre kinking: Part I: FE implementation," Composites Part A: Applied Science and Manufacturing, Vol. 37 (5), pp 766-777, 2006.