DIGIMAT for

AEROSPACE

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Materials: Carbon Fiber Reinforced Plastics, Carbon-Epoxy, Carbon-PEEK, Thermoplastics, Thermosets, Carbon nanotubes.
e-Xstream Technology: DIGIMAT, Digimat-MF, Digimat-FE, Digimat to Abaqus.
Complementary CAE Technology: Abaqus/Standard, Abaqus/Explicit.
Industry: Material Suppliers, Aeronautical Industries.
Capabilities: Modeling mechanical behavior of composites with Carbon fibers:

- Temperature dependent materials,
- Failure properties,
- Percolation,
- Multilevel homogenization,
- Multilayer RVE.

Performance: Mechanical, electric and thermal properties, strength, barely visible damage.
Case Study: Multi-scale modeling of Ultra LightWeight (ULW) antenna (ESA), impact test.
Related Documents:
DIGIMAT product sheet
DIGIMAT for ENGINEERING PLASTICS
DIGIMAT for NANO-COMPOSITES

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EXECUTIVE SUMMARY

e-Xstream engineering is a software and engineering services company, 100% focused on advanced material modeling technology. We help our customers reducing their development costs and the time needed to bring innovative and high-quality products to the market. For a general introduction to the DIGIMAT software suite, please refer to the DIGIMAT product sheet. Here we will limit ourselves to topics particular to aeronautical materials, *i.e.* composites filled with Carbon fibers, which present a very high stiffness to weight ratio.

As the DIGIMAT software suite is dedicated to the modeling of composite materials in a broad sense, extended functionality has been added specifically to model effects encountered within aeronautical materials:

- Influence of volume fraction,
- Size effect: influence of the aspect ratio on the macroscopic stress-strain curve,
- Temperature dependent properties,
- Failure properties.

Depending on the composite specifications, some or all of the above mentioned effects may be of importance. These effects are explained in detail in the section below, "Modeling aeronautical materials with Digimat-MF". Some of these special modeling features are demonstrated by means of a complex industrial Case Study consisting in the modeling if ULW antenna, including Digimat-MF and Digimat-FE analyses.

Digimat-MF and Digimat-FE are complementary tools, useful for aeronautical materials modeling. Digimat-MF, which is based on nonlinear semi-analytical homogenization theory, offers accurate and efficient predictions at the macroscopic scale (*i.e.* composite level). The results at the microscopic scale (*i.e.* for the constituent phases) are averaged. Digimat-FE, based on direct nonlinear Finite Element Analysis (FEA) of material Representative Volume Element (RVE), offers accurate local predictions at both the macroscopic and the microscopic scales. The time needed to build and solve a Digimat-FE model is much larger than that for Digimat-MF. The software and technology are backed up by a team of engineers with a strong expertise in nonlinear finite element analysis, material modeling and multi-scale analysis of reinforced plastics.

MODELING AERONAUTICAL MATERIALS

Digimat-MF

Digimat-MF is a user-friendly micromechanical material modeling software where the user specifies the material behavior of the phases, the microstructure morphology and the loading applied to the composite material. Digimat-MF then predicts the composite's mechanical, thermal, thermo-mechanical and electrical behavior based on homogenization techniques (Mori-Tanaka or Interpolative Double Inclusion models). Filler particles are assumed to have an ellipsoidal shape defined by the aspect ratio (AR = Length/Diameter). This way, spherical particles, platelets and fibers can be modeled correctly, while even for non-ellipsoidal particles (such as a stack of clay sheets) accurate results can also be obtained. One or more phases of inclusions can be defined, *e.g.* regular Carbon fibers and mineral nano-fillers in a polymer matrix.

Generally, in the case of multi-phase composites, a homogenization method should account for different factors, such as the thermo-mechanical phase behavior, the volume fraction and the shape of the reinforcements. However most of the commonly used models, like Voigt and Reuss or Halpin-Tsai models, describe the composite behavior without using of information on the shape of the reinforcements. These types of models try to estimate bounds for the composite properties by a strain energy approach. More advanced methods, based on Eshelby's solution (like Mori-Tanaka or Double Inclusion), have the advantage of being more general and more accurate because they explicitly take into account the shape of the different inclusion phases.

The following capabilities extend the DIGIMAT functionalities towards modeling aeronautical materials:

- ## Influence of volume fraction

  In order to illustrate the capabilities and results obtained with Digimat-MF, a fibers/matrix combination has been modeled with a varying volume fraction and further been compared with the different models available in the literature. We concentrate here on the transverse Young's modulus (E2) and the shear modulus (G12), since all these models give nearly identical results for longitudinal modulus. The composite under investigation is made of Carbon T300 3K with a volume fraction of 55% in an Epoxy F593. Experimental values are from ESA Structural Material Handbook (1). The mechanical properties of Epoxy F593 are the following: E = 2.96 GPa and ν = 0.35. Figures 1 and 2 respectively illustrate the evolution of the transverse Young's modulus (E2) and the shear modulus (G12) with respect to the carbon fibers volume fraction in the composite.

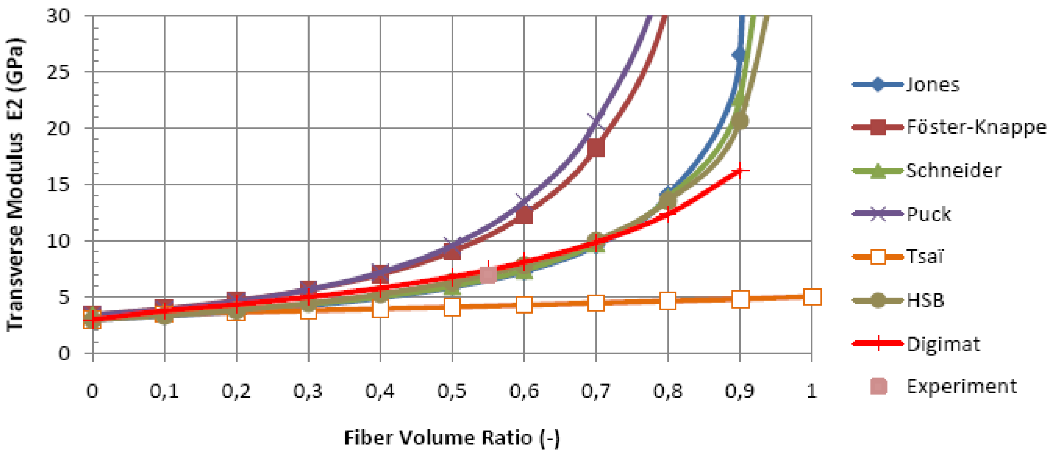


Figure 1: Evolution of the transverse Young's modulus (E_2) as a function of the fiber volume fraction; comparison of Digimat-MF computations with micromechanical models (source: ESA Structural Material Handbook (1)).

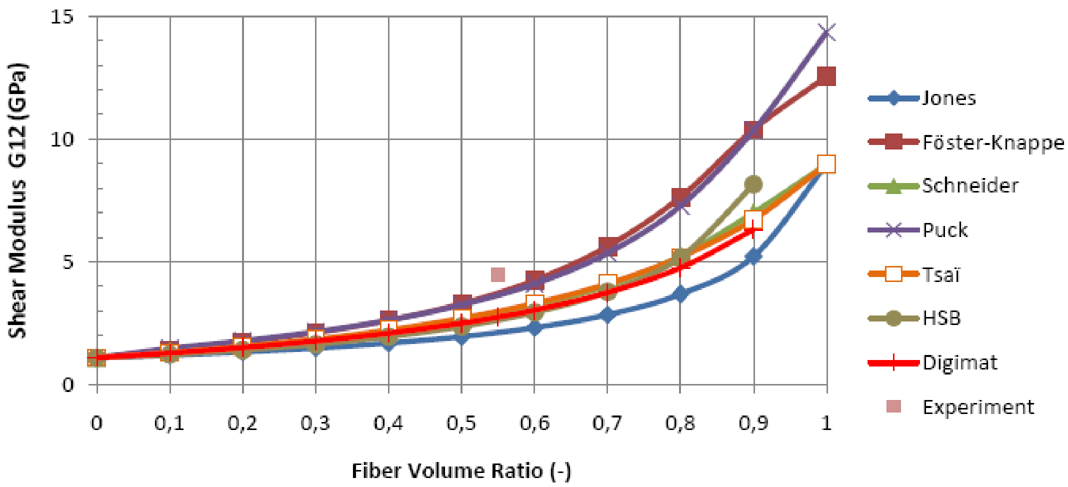


Figure 2: Evolution of the shear modulus (G_{12}) as a function of the fiber volume fraction; comparison of Digimat-MF computations with different micromechanical models (source: ESA Structural Material Handbook (1)).

- ## Size effect: influence of the aspect ratio on the macroscopic stress-strain curve

  Digimat-MF homogenization techniques do not consider an absolute filler size but only use the filler's aspect ratio (constant, or in the form of a distribution) and the filler mass or volume fraction. Figure 3 displays the macroscopic stress-strain response of a PEEK matrix filled with unidirectional carbon fibers. The aspect ratio is taken as a free parameter. Note that the PEEK matrix is modeled using an elastoplastic material model.

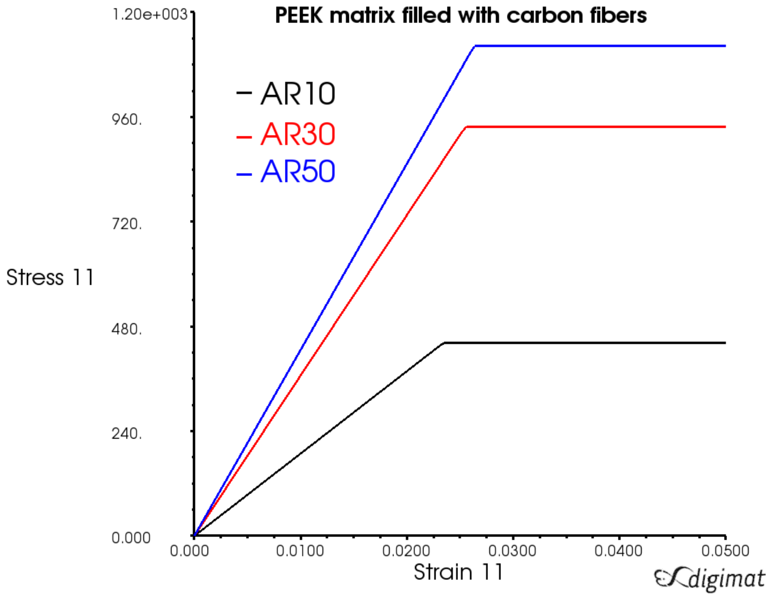


Figure 3: Macroscopic stress-strain curves for different aspect ratios in the case of carbon-PEEK composite.

- Temperature-dependent materials

It is well known that aeronautical materials have to deal with varying temperatures. In order to be able to take such effects into account, temperature-dependent properties are needed. The evolution of the material coefficients with respect to the temperature can be integrated in DIGIMAT either for the matrix, the fibers or both. Let us consider an epoxy matrix modeled as a thermo-elastic material with a reference temperature of 149°C filled with carbon fibers. The carbon fibers have isotropic elastic properties combined with transversally anisotropic thermal properties. Properties of both materials are respectively summarized in Tables 1 and 2.

Table 1: Thermo-elastic properties of the epoxy matrix.

Temperature (°C)	-190	24	149
E (GPa)	7.9	3.4	2.4
ν (-)	0.47	0.39	0.48
α (10^{-6} /°C)	32	45	51

Table 2: Thermo-elastic properties of the carbon fibers.

Temperature (°C)	-190	24	149
E (GPa)	395	276	208
ν (-)	0.3	0.3	0.3
G (GPa)	152	106	80
α_{11} (10^{-6} /°C)	-0.4	-0.4	-0.4
α_{22} (10^{-6} /°C)	6.6	6.6	6.6
α_{33} (10^{-6} /°C)	6.6	6.6	6.6

From then on, if a thermo-mechanical loading is applied to the composite, it is possible to assess the evolution of the strain, the stress or even the Coefficient of Thermal Expansion (CTE) either per phase or for the composite with respect to the temperature. Figure 4 presents the evolution in the 3 directions of the composite's CTE as a function of the temperature.

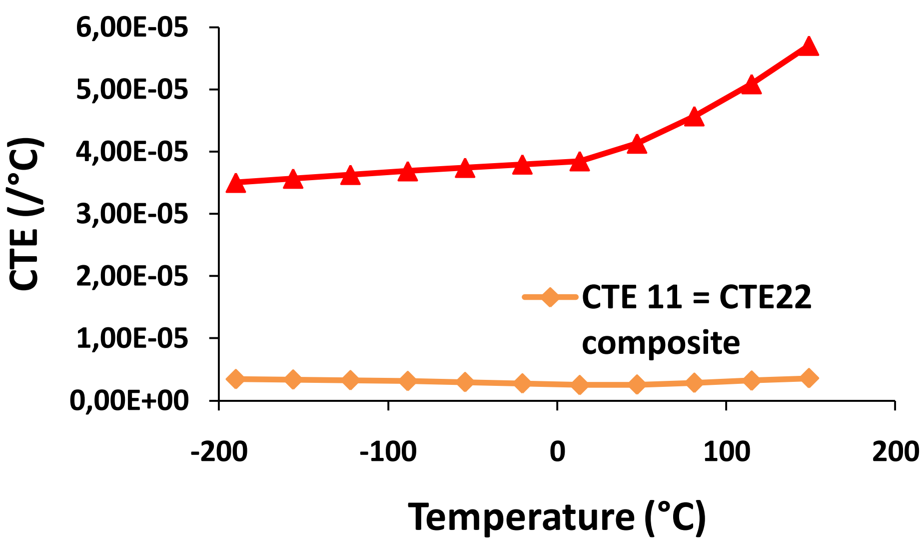


Figure 4: Evolution of the composite's CTE as a function of temperature.

- Failure properties

Digimat-MF enables the user to deal with failure problems via the use of failure indicators which can be assigned at the phase, composite or even pseudo-grain level (the latter concept is currently limited to misaligned inclusions). Failure indicators can be related to a critical stress or strain in local, global or tensor's principal axes. Other models are available in Digimat-MF as well, such as Tsai-Hill, Azzi-Tsai-Hill, Tsai-Wu, Hashin-Rothem and Hashin. Moreover, more advanced concepts such as the Kelly-Tyson estimator and the First-Pseudo Grain Failure (FPGF) indicator are available.

- Percolation

When studying the electrical conductivity of carbon-filled materials, the percolation effect is of great importance. This effect is typically observed in a nearly insulating polymer matrix reinforced with highly conductive inclusions (for example Carbon Nanotubes (CNT)). Between two inclusions closer than a critical distance (tunneling distance), electron "jumps" may occur from one inclusion to another through the polymer matrix. This effect has a great influence on the electrical conductivity of the composite when the volume fraction of filler is greater than a certain threshold, the so-called percolation threshold. When the volume fraction reaches this threshold, a continuous path of inclusions is formed and the composite becomes electrically conductive. Typical applications for this effect include composites with good antistatic or electromagnetic shielding properties.

A percolation model has been developed in Digimat-MF to be able to accurately simulate this effect. Figure 5 illustrates this model in the case of a PE matrix reinforced with carbon inclusions. The composite's conductivity increases by several orders of magnitude when the volume fraction of inclusions reaches the percolation threshold.

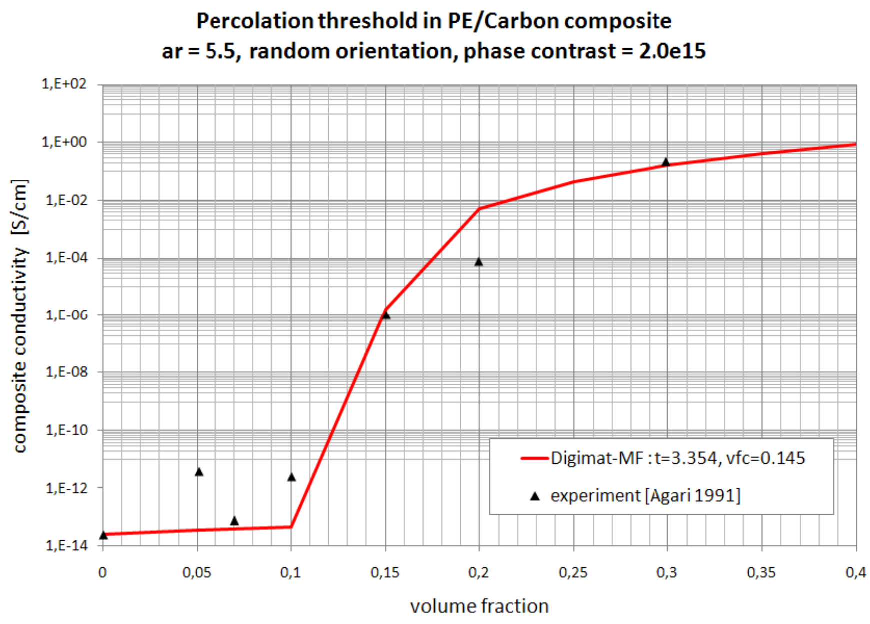


Figure 5: Illustration of the percolation model developed in Digimat-MF, and comparison to experimental data.

- Multi-scale homogenization

  DIGIMAT also enables the user to perform multi-scale homogenization. For instance, a 3-scale modeling approach can be used to model the thermo-elastic behavior and strength of ultra-Lightweight Antenna using an original 3-scale modeling approach. The first scale is the scale of the yarn, made of long, uniaxial carbon fibers bonded by a resin matrix. The second scale is the scale of the fabric. In this step, each yarn's heterogeneous material is replaced at the macroscopic level with a fictitious homogeneous material whose effective properties are determined from the previous step. A unit cell is isolated; FE simulations are conducted in order to extract macroscopic properties of an equivalent, homogeneous shell. The third scale is the scale of the complete antenna. The properties of the equivalent homogeneous shell computed in the second step will be used.

Finally, Digimat-MF offers an array of other functionalities which are relevant to aeronautical materials modeling: the ability to specify coatings (real or representative of one or more nano-effects), the ability to specify absolute coating thickness to investigate size-effects, the ability to apply Multi-Level homogenization (homogenize A with B, then AB with C, then ABC with D, etc).

Digimat-FE

Digimat-FE is a micromechanical material modeling software that uses a direct, realistic finite element representation of a representative volume element (RVE) of the composite's microstructure. Digimat-FE is complementary and fully interoperable with Digimat-MF. The main advantages of Digimat-FE with respect to Digimat-MF are:

1. The possibility to generate very complex RVEs such as multilayer RVE with various fiber orientations and/or volume fractions;
2. Use periodic modeling regarding both the geometry and the boundary conditions;
3. Compute the actual distribution of the local fields at the micro scale (*i.e.* in each phase of the composite) in addition to the macroscopic response of the composite;
4. Model debonding between the fibers and the matrix.

The CPU time needed to set-up and run a Digimat-FE model is much larger than that for an equivalent Digimat-MF analysis, while the macroscopic response predictions of both approaches are comparable. Digimat-MF should thus be used for the initial analyses, while Digimat-FE can be used for verification and deeper analysis of microscopic material response behavior.

Digimat-FE can be used to generate very realistic RVE microstructures, which can be exported in *step* or *iges* formats. Digimat-FE is interfaced with Abaqus/CAE for the automatic meshing of the RVE microstructure geometry as well as the definition of materials, loads and boundary conditions. Abaqus/Standard is then used to solve the nonlinear FE model. The final results can be post-processed as a regular Abaqus FEA solution or within Digimat-FE for the micromechanical results, such as the probability to reach a given stress, strain or failure indicator, for a given phase or for the composite.

Particular usages of Digimat-FE for aeronautical materials modeling include:

- **Multilayer RVE**

  Digimat-FE offers a lot of functionalities to design a microstructure of choice. One of the options is to generate a multilayer RVE. The user can specify the desired number of layers, the orientation of the fibers (fixed, random 2D, random 3D or given by an orientation tensor) and the thickness and orientation of each layer. Figure 6 displays a multilayer RVE composed by an epoxy matrix filled with 40% of carbon fibers and defined by 8 layers as follows: $[0, 45, 90, -45]_S$ (angles are in degrees).

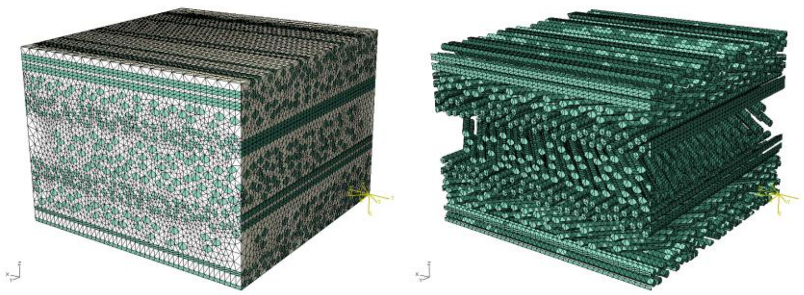


Figure 6: Multilayer $[0, 45, 90, -45]_S$ RVE.

- **Periodic modeling**

  Periodic geometries and boundary conditions can easily be created and applied via the user-friendly interface of Digimat-FE. Such a modeling approach, though heavier in terms of computations, turns out to be more accurate and representative.

- **Per phase stress-strain distribution**

  Digimat-FE enables to assess the distributions of the stress and strain per phase. This means that the user could study the RVE failure through the analysis of the failure risk per phase. For instance, let a shear loading be applied such that $\epsilon_{xy} = 0.5\%$. Figure 7 displays the mapping of the von Mises equivalent stress within the carbon fibers. The post-processing of the Abaqus computation can be performed with Digimat-FE to assess the per phase stress/strain distribution as depicted in Figure 8. Indeed, Figure 8 presents the evolution of the probability with respect to the stress (minimal and maximal principal stresses, von Mises stress…) within the carbon fibers (a) and within the matrix (b).

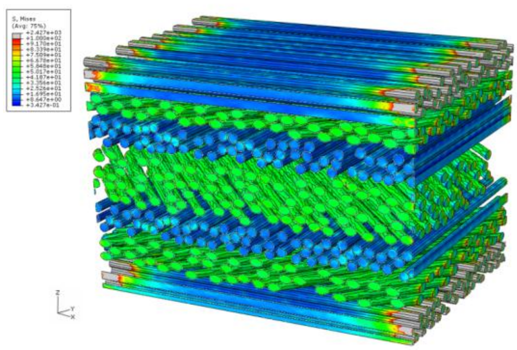


Figure 7: von Mises stress distribution within the carbon fibers.

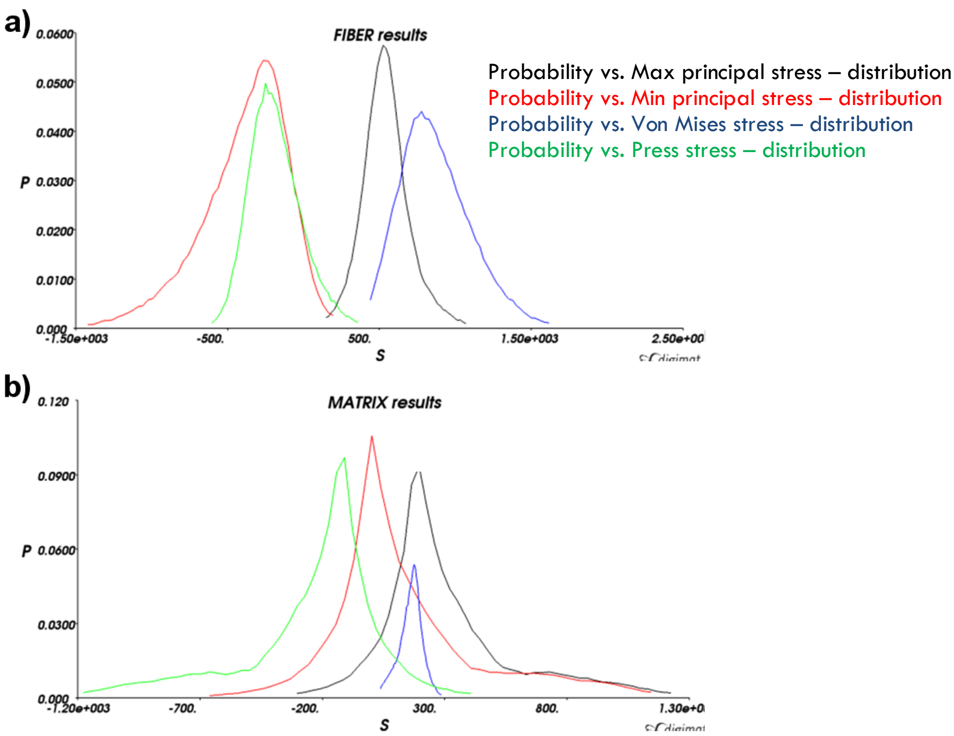


Figure 8: Stress distribution within the fibers (a) and the matrix (b).

- Particle-matrix interface and particle-particle interaction

  The materials and microstructure definition of Digimat-MF is directly translated into Digimat-FE where it is ready to be used by the RVE geometry generator. In other words, any real or representative coatings, effective particle properties or effective cluster materials are transferred automatically from Digimat-MF to Digimat-FE. In case of coatings, the RVE geometry generator will produce a microstructure geometry including the coating (if any) and obeying the mass or volume fraction of the phases as closely as possible. Moreover, Digimat-FE is able to generate geometries where the inclusions or the coatings intersect to a specified degree and also geometries with clusters of particles (defined by the number of clusters and the degree of clustering). This allows an enhanced modeling of interfaces and interactions.

- Inclusion-matrix debonding

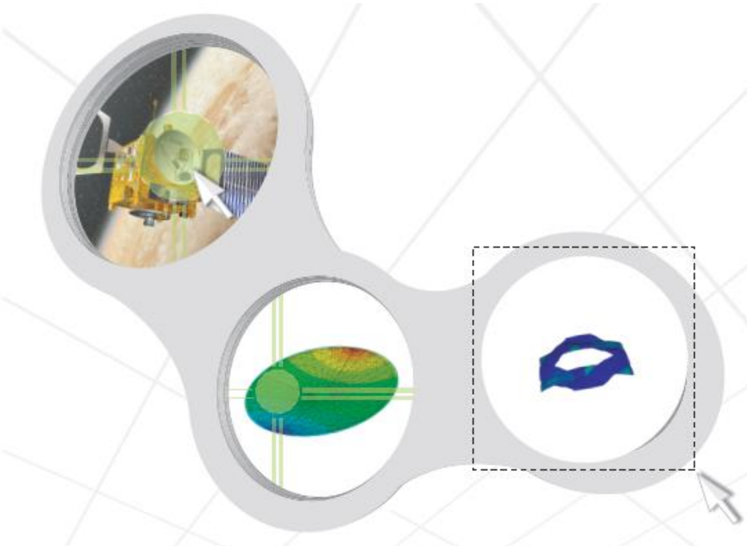
  Digimat-FE can be used to model inclusion-matrix debonding. Indeed, two different approaches exist: debonding at interface and debonding at inter-phase. In the Digimat-FE terminology, the interface is the surface (*i.e.* 2D, no thickness) between an inclusion and the matrix. The inter-phase is the matrix zone in the vicinity of an inclusion that is influenced by the presence of the inclusion and thus has a finite thickness. At the level of the finite element model, allowing debonding between the inclusions and the matrix is a good way to avoid unreal element distortion in the matrix in the vicinity of the fiber tips. A cohesive zone material model is used to model the material behavior in the zone between the inclusion and the matrix.

In conclusion, Digimat-FE supports and expands the functionalities of Digimat-MF and offers a wide variety of tools for the modeling of aeronautical materials. The two modules Digimat-MF and Digimat-FE are a complementary set of tools for the analysis of any composite material.

Case Study: Multi-scale modeling of Ultra-lightweight (ULW) antenna (ESA)

This case study deals with an original multi-scale modeling approach regarding Triaxial Woven Fabrics (TWF). TWF composites are made up of three sets of yarns woven at 60 degree angles. Herein, the modeling of the thermo-elastic behavior and strength of a satellite antenna reflector made of TWF has been performed via a 3-scale modeling approach:

- The scale of the TWF yarn, modeled using mean-field homogenization theory,
- The scale of the fabric, modeled using a finite element model of a unit cell,
- The scale of the complete antenna.



First scale: micro-mechanical thermo-elastic model of the yarn - analysis with Digimat-MF

The TWF yarn is a composite made of long, uniaxial high modulus carbon fibers bonded by a resin matrix. The two main matrix materials used with TWF are epoxy and cyanate ester. The aim of this first step is to compute the thermo-mechanical behavior of this composite, based on different factors, like the thermo-mechanical phase behavior, the volume fraction and the shape of the reinforcing phase. One option is the commonly used models, like Voigt and Reuss or Halpin-Tsai models. These models describe the composite behavior without making use of information on the shape of the reinforcements. They try to estimate bounds for the composite properties by a strain energy approach. A second option is to use more advanced methods, based on the Eshelby solution (like Mori-Tanaka or Double Inclusion). These methods have the advantage of being more general and more accurate as they explicitly take into account the shape of the different reinforcements. Digimat-MF has been involved in the modeling of the first scale, *i.e.* the TWF yarn and requires the definitions of the material behavior and morphology of each phase.

Table 3 summarizes the Digimat-MF results with different models commonly found in the literature. This comparison is applied to the case of a Cyanate ester 954-2A matrix filled with T300 carbon fibers. The volume fraction of the carbon fibers is equal to 67%. Both the Föster-Knappe and Puck models should give bad predictions, since these are semi-empirical models derived from experimental data for glass/epoxy composites. The other four models, Jones, Schneider, Tsai and HSB should give better results.

Table 3: Comparison of different homogenization models.

	E1 (GPa)	E2 (GPa)	n12	n23	G12 (GPa)	G23 (GPa)
DIGIMAT	349,590	12,590	0,252	0,515	4,505	4,150
CCM	349,586	10,222	0,252		2,829	
Mixture	349,555	14,890	0,259		4,506	
Jones	349,555	9,006	0,259		3,256	
Föster-Knappe	349,555	15,213	0,259		6,478	
Schneider	349,555	3,379	0,259		4,708	
Puck	349,555	17,737	0,259		6,108	
Halpin-Tsaï	349,555	12,878	0,259		4,864	
HSB	349,555	12,581	0,259		4,536	

For complete validation, comparison to experimental data has to be included. The problem is that these data are quite difficult to find and, most importantly, often show important variations (due to varying manufacturing conditions, testing procedures ...). Two sets of data have been used for the validation of the homogenization methods used in DIGIMAT. The first set comes from the ESA Structural Material Handbook (Table 4) and the second set is from the Hexcel datasheets (Table 5).

Table 4: Comparison of experimental and computed properties (stiffness and failure) in the case of a Epoxy F593-7 matrix filled with Carbon T300. Date from ESA Structural Material Handbook (1).

	Exp.	DIGIMAT
0° Strength (MPa)	1616	1962
0° Modulus (MPa)	135000	129510
90° Strength (MPa)	40	88.4
90° Modulus (MPa)	7000	7512

Table 5: Comparison of experimental and computed properties (stiffness and failure), data from Hexcel products datasheets.

	M76/M55J		954-6/M55J		954-3/M55J		954-3A/M55J	
	Exp.	DIGIMAT	Exp.	DIGIMAT	Exp.	DIGIMAT	Exp.	DIGIMAT
0° Strength (MPa)	2158	2424	2165	2423	2303	2420	2027	2422
0° Modulus (MPa)	338000	325600	321000	325520	324000	325140	323000	325350
90° Strength (MPa)	36	235.1	40	143.7	35	87.16	x	85.8
90° Modulus (MPa)	6500	11734	6200	11266	6200	8908	x	10295

The comparison between the experimental and the computed stiffness exhibits a good agreement regarding the longitudinal modulus. For the transverse modulus, the values computed by DIGIMAT are much stiffer than the experimental values. The same conclusion holds for strength value: quite good agreement for longitudinal tensile strength, larger differences for transverse tensile strength. The explanation is due to the sensitivity of the matrix to environmental conditions (temperature, humidity, moisture absorption, micro-cracking). On the contrary, the fibers show little sensitivity to environmental conditions (at least in the range considered here). Since the longitudinal properties are governed by the fiber properties and the transverse properties by the matrix properties, it is normal to have larger differences between the experimental and the computed values for the transverse properties than for the longitudinal ones.

To explain in more detail this discrepancy between experimental and computed transverse tensile strength, it is interesting to look at the failure modes that take place. It appears that the dominant failure mode depends on temperature (2). Another very important parameter is the presence of an interphase between the fiber and matrix. This interphase is nearly always present and can have several origins (chemical reaction zone, diffusion zone, coated fibers, damage zone due to thermal stresses caused by manufacturing process …). It has been shown that such an interphase can greatly affect the macroscopic failure behavior of unidirectional composites (3).

Second scale: Unit cell of TWF Fabric – FE analysis

In this step, each yarn's heterogeneous material is replaced at the macroscopic level with a fictitious homogeneous material whose effective properties are determined from the previous step. A unit cell is isolated and FE simulations are conducted in order to extract macroscopic properties of an equivalent, homogeneous Kirchhoff shell. The behavior of this equivalent shell can be fully described by means of a single 6x6 matrix, the ABD matrix.

The original three-dimensional problem is thus reduced to a two-dimensional problem in the mid-thickness surface. Mid-plane strains and curvatures are related to the forces and moments per unit length through the ABD matrix.

$$\begin{pmatrix} \underline{N} \\ \underline{M} \end{pmatrix} = \begin{pmatrix} [A] & [B] \\ [B] & [D] \end{pmatrix} \begin{pmatrix} \underline{\varepsilon^0} \\ \underline{K} \end{pmatrix}$$

Several finite element models of a unit cell of TWF have been built. In this paper, we will concentrate on the SK-802 fabric (manufactured by Sakase Adtech). Several different unit cells are possible, but the aim is to choose a unit cell that is representative, as small as possible and not too complex, to avoid making the definition of the periodic boundary conditions overly complex. Taking into account all these constraints, we have opted for a rectangular unit cell. The unit cell was built and meshed using Abaqus/CAE. We started by creating a single yarn by sweeping a cross section along a sweep path. Six copies of this yarn were then assembled together to form a unit cell. This approach is quite easy, but has some limitations.

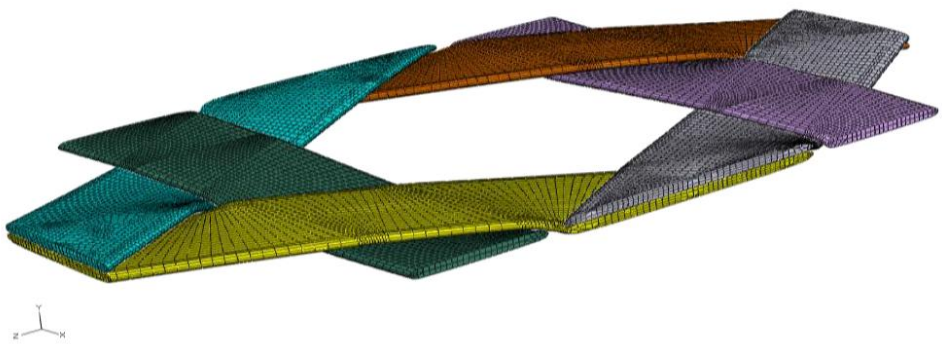


Figure 9: Finite element model of the TWF unit cell.

To derive the ABD matrix, six deformations are imposed on the unit cell, in six separate FE analyses, using periodic boundary conditions (ref. 2 and 3). In each of these analyses, one of the six average strain/curvature is non zero, the five others are set to zero.

For each FE analysis, the output is a set of reaction forces/moments and corresponding displacement/rotations at the 8 reference nodes. With these outputs, it is possible to compute all the entries of the ABD matrix. In this work, we used the idea presented by Pellegrino et al (ref. 3) of using virtual work. The following results were obtained for the ABD matrix of a SK-802 fabric (made of 1-K T300 carbon fiber) impregnated with Hexcel 8552 epoxy resin.

We used the experimental data from Pellegrino et al. (ref. 5) for validation. They performed experimental measurements of the main engineering constants of a SK802+H8552. The comparison presented in table 6 shows that the proposed modeling approach gives results in good agreement with the experiment.

Table 6: Comparison of computed and experimental values for engineering constants of SK802+H8552.

	Computed values	Experimental values (average)
Extensional stiffness S_x (N/mm)	2111.87	2145
Poisson's ratio ν_{xy}	0.588349	0.586
Shear stiffness S_{xy} (N/mm)	673.4458	777.12
Bending stiffness D_x (N/mm)	2.640621	2.077

Third scale: application to a complete satellite antenna model

A finite element model of this reflector has been built, using the computed ABD matrix of the equivalent shell as material properties. This means that simple triangular or rectangular shell elements can be used. The finite element model was submitted to 4 thermal loadings: two uniform low temperatures (-150°C and 170°C), a temperature gradient through the thickness and a temperature gradient in the X direction. These load cases correspond to actual in orbit situations when the reflector is exposed to the sun in different ways. The main output variables of interest in these simulations are the displacements. In orbit, a small distortion can result in a beam misalignment of several hundreds of kilometers down on the earth. It appeared that the most critical loading is the uniform high temperature case. Results obtained for this case are presented in Figure 10.

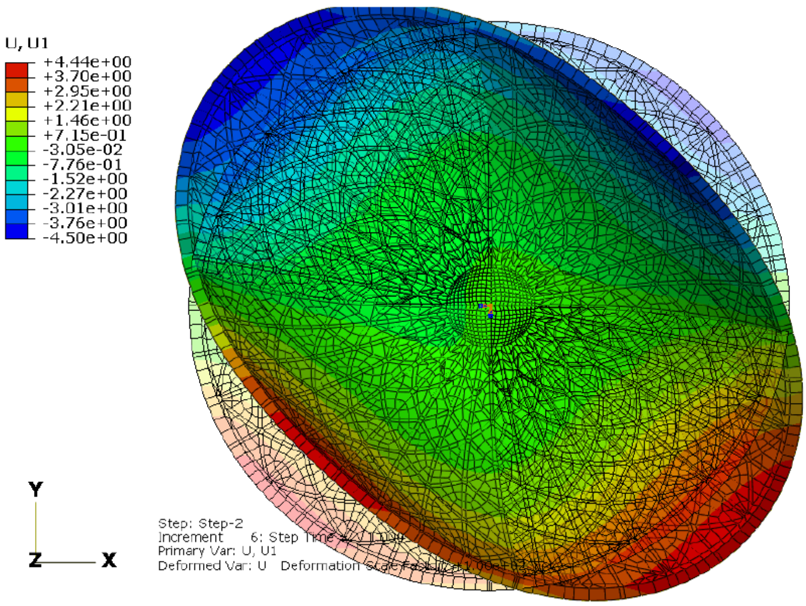


Figure 10: U1 displacement for the uniform high temperature case (scale factor 100).

Case Study: Modeling steel ball impacts and predicting impact damage initiation in composite structure

Laminated polymer composites have found widespread use in the design of aerospace structures. These materials offer excellent in-plane performance, but are subject to possible damage when severely loaded out-of-plane, such as in the case of localized impact. Damage resulting from such impacts is usually barely visible and takes the form of subsurface matrix cracks, backside fiber failure, and delaminations (ref 4).

This case study is devoted to the impact of flexible composite structures by high velocity steel ball (18-37 $m.s^{-1}$).

Keywords: *Impact, barely visible damage, aerospace structure, quasi-static loading, dynamic loading.*

FE model

The impactor, *i.e.* the steel ball, were modeled using 6000 4-node linear tetrahedral elements (*C3D4*) whereas the plate consisted in a 24 layers composite shell involving 600 4-node quadratic elements with reduced integration (*S4R*) (Figure 11).

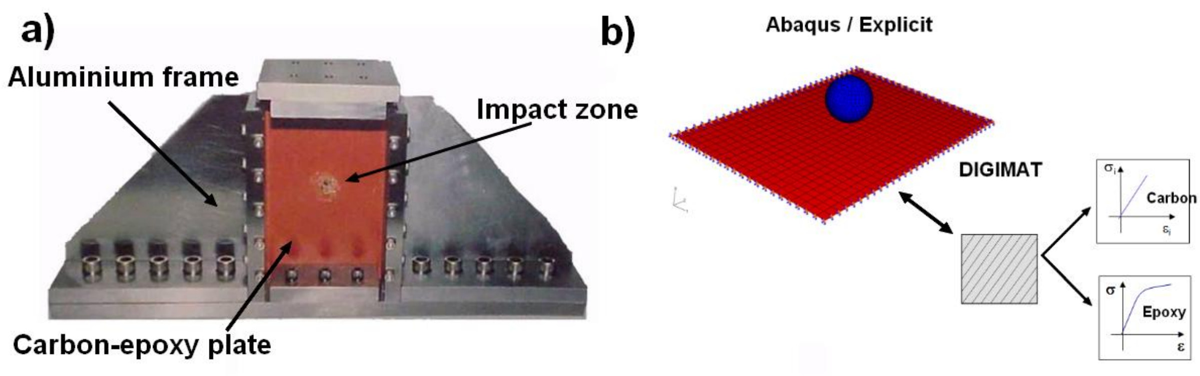


Figure 11: (a) Experimental setup including the composite panel target; (b) Meshes of the steel ball and the composite plate.

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The composite is made of 24 layers with a $[45/90/-45/0]_{3S}$ sequence and consist in Carbon AS4 fibers bonded in an elasto-plastic epoxy matrix. Properties of both materials are summarized in the Table 7.

Table 7: Mechanical properties of the Carbons-Epoxy composite constituents.

Epoxy		Carbon AS4	
Young's modulus	1300 MPa	Longitudinal Young's modulus	228000 MPa
Yield stress	22.5	Transverse Young's modulus	6220 MPa
Isotropic hardening	Exponential law	Transverse shear modulus	7600 MPa
		Tensile strength	4278 MPa

Failure indicators, based on the maximum stress, have been added to the model both at the matrix and fibers scales. Indeed, regarding the fibers, failure indicators are related to the maximum axial stress whereas in the case of the matrix, no direction has been favored.

Results

Impact test

An impact test with Abaqus / Explicit was performed with a ball velocity of 37 $m.s^{-1}$ equivalent to an energy of 40 J. Figure 12a evidences a von Mises stress equal to 0 MPa within the upper ply after impact. However, Figure 12b which displays the evolution of the failure indicator as a function of the time, clearly highlight that damage occurs within the composite.

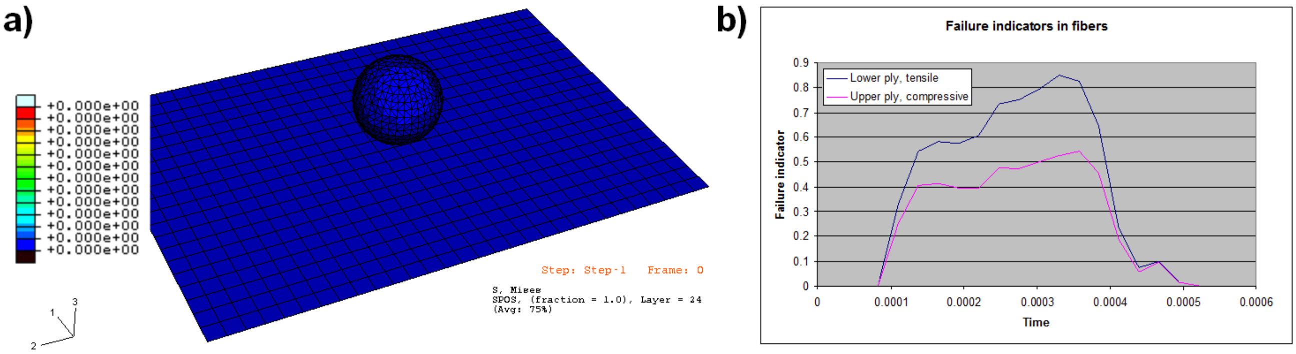

Figure 12: von Mises stress in the upper ply (a) and failure indicators in both lower and upper plies as a function of the time during at steel ball impact test at 37 m.s-1.

Quasi-static loading / cyclic loading

Although no visible deformation is evidenced at the macro level, an important amount of plastic strain occurred within the matrix phase which can be related to damage as shown Figure 13b.

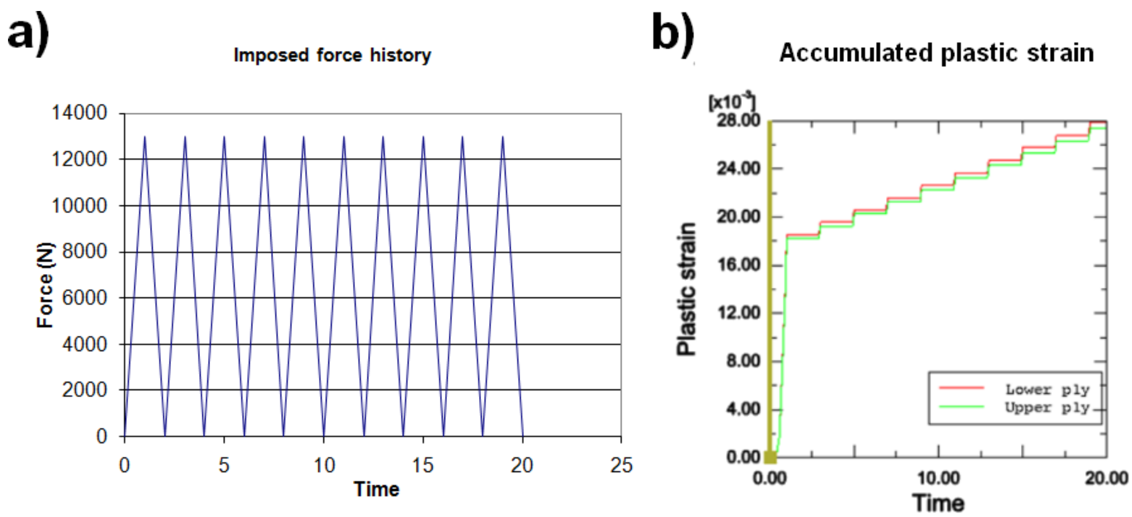

Figure 13: (a) Imposed for a history; (b) evolution of the accumulated plastic strain in the matrix as a function of the time.

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