Multi-Scale Modeling of the Impact and Failure of Fiber Reinforced Polymer Structures using DIGIMAT to LS-DYNA Interface

Authors:
L. Adam, R. Assaker & R. Ramaya
e-Xstream engineering S.A.
7, Rue du Bosquet. B-1348 Louvain-la-Neuve.
Belgium

Correspondence:
R. Assaker
e-Xstream engineering S.A.
Phone : +32 (0)10 866425
Fax : +32 (0)10 840767
Email : Roger.Assaker@e-xstream.com

ABSTRACT:

This paper deals with the prediction of the overall behavior of polymer matrix composites and structures, based on mean-field homogenization. We present the basis of the mean-field homogenization incremental formulation and illustrate the method through the analysis of the impact properties of fiber reinforced structures. The present formulation is part of the DIGIMAT [1] software developed by e-Xstream engineering. An interface between LS-DYNA and DIGIMAT was developed in order to perform multi-scale FE analysis of these composite structures taking into account the local, anisotropic, nonlinear and strain-rate dependent behavior of the material.

Impact simulations are performed on glass fiber reinforced polymer structures using DIGIMAT interface to LS-DYNA. These analyses enable to highlight the sensitivity of the impact properties to the fibers' concentration, orientation and length.

Keywords:
Multi-scale material modeling, micro-macro material modeling, composite materials, fiber reinforced materials.

INTRODUCTION

The accurate linear and nonlinear modeling of complex composite structures pushes the limits of finite element analysis software with respect to element formulation, solver performance and phenomenological material models. The finite element analysis of injection molded structures made of nonlinear and/or time-dependent anisotropic reinforced polymer is increasingly complex. In this case, the material behavior can significantly vary from one part to another throughout the structure and even from one integration point to the next in the plane and across the thickness of the structure due to the fiber orientation induced by the polymer flow. The accurate modeling of such structures and materials is possible with LS-DYNA using LS-DYNA's Usermat subroutine to call the DIGIMAT micromechanical modeling software [1]. In addition to enabling accurate and predictive modeling of such materials and structures, this multi-scale approach provides the FEA analyst and part designer with an explicit link between the parameters describing the microstructure (e.g. fiber orientation predicted by injection molding software and the final part performance predicted by LS-DYNA).

THEORETICAL BACKGROUND OF HOMOGENIZATION

In a multi-scale approach, at each macroscopic point $\bar{x}$ (which is viewed at the microscopic level as the center of a representative volume element (RVE) of the material under consideration), we know the macroscopic strain $\bar{\varepsilon}$ and we need to compute the macroscopic stress $\bar{\sigma}$ or vice-versa. At the microscopic level, we have an RVE of domain ω and boundary $\partial\omega$. It can be shown that if linear boundary conditions are applied on the RVE, relating macroscopic stresses and strains is equivalent to relating average stresses $\langle\sigma\rangle$ to average strains $\langle\varepsilon\rangle$ over the RVE. The homogenization procedure is divided in three steps (see Figure 1). In the first step, called the localization step, the given macroscopic strain tensor is localized in each phase of the composite material. In the second step, constitutive laws are applied for each phase and a per phase stress tensor is computed. The phases' stress tensors are averaged in the last step to give the macroscopic stress tensor. The composite behavior will depend explicitly on the phase behavior, the current inclusion shape and the current inclusion orientation.

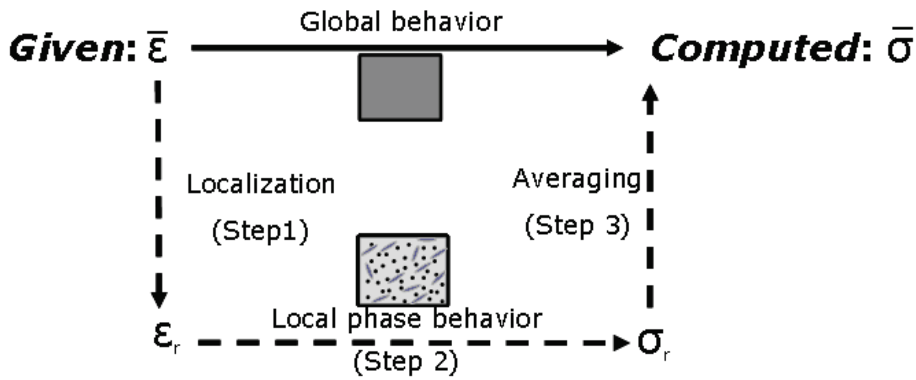

Figure 1: Homogenization - General scheme

Homogenization of a two-phase composite

Let's consider a two-phase composite where inclusions (denoted by subscript 1) are dispersed in a matrix (subscript 0). The matrix, which extends on domain ω_0, has a volume V_0 and volume fraction $v_0 = {V_0}/{V}$, where V is the volume of the RVE. The inclusion phase, which extends on domain ω_1, has a total volume V_1 and a volume fraction $v_1 = {V_1}/{V} = 1 - v_0$. We then define the following volume averages, respectively over the RVE and both phases:

$$\langle f \rangle \equiv \frac{1}{V}\int_{\omega} f(x,\bar{x})dV \;,\; \langle f \rangle_{\omega_r} \equiv \frac{1}{V_r}\int_{\omega_r} f(x,\bar{x})dV_r, \quad \mathrm{r} = 0{,}1 \qquad \text{(Eq. 1)}$$

and where the integration is carried out with respect to the micro coordinate x. In the following, dependence on macroscopic coordinates $\bar{x}$ will be omitted for simplicity. It is easy to check that these averages are related by:

$$\langle f \rangle = v_1 \langle f \rangle_{\omega_1} + v_0 \langle f \rangle_{\omega_0}. \qquad \text{(Eq. 2)}$$

The per phase strain averages are related by a strain concentration tensor B^{ε} as follows:

$$\langle \varepsilon \rangle_{\omega_1} = B^{\varepsilon} \langle \varepsilon \rangle_{\omega_0}. \qquad \text{(Eq. 3)}$$

Various homogenization models were proposed in the literature and differ in the expression of B^{ε} . The per phase strain averages are related to the macroscopic strain $\bar{\varepsilon} = \langle \varepsilon \rangle$ by:

$$\langle \varepsilon \rangle_{\omega_0} = \left[v_1 B^{\varepsilon} + (1 - v_1) I \right]^{-1} : \langle \varepsilon \rangle$$

and

$$\langle \varepsilon \rangle_{\omega_1} = B^{\varepsilon} : \left[v_1 B^{\varepsilon} + (1 - v_1) I \right]^{-1} : \langle \varepsilon \rangle \qquad \text{(Eq. 4)}$$

Except for the simplest models (e.g. Voigt model, which assumes uniform strains over the RVE and Reuss model, which assumes uniform stress), homogenization models are based on the fundamental solution of Eshelby [3,2]. That solution allows solving the problem of a single ellipsoidal inclusion (I) of uniform moduli c_1 which is embedded in an infinite matrix of uniform moduli c_0. Under a remote uniform strain $\bar{\varepsilon}$, it is found that the strain field in the inclusion is uniform and related to the remote macroscopic strain by:

$$\varepsilon(x) = H^{\varepsilon}(I, c_1, c_0) : \bar{\varepsilon} \quad \forall x \in (I) \qquad \text{(Eq . 5)}$$

where the single strain concentration tensor H^{ε} has the following expression :

$$H^{\varepsilon}(I, c_1, c_0) = \left[I + P(c_0, c_1) : (c_1 - c_0) \right]^{-1} \qquad \text{(Eq. 6)}$$

and where $P(c_0, c_1) = \xi(I, c_0) : (c_0)^{-1}$ denotes the polarization tensor which is evaluated from Eshelby's tensor $\xi(I, c_0)$, which can be computed analytically in the simplest case and numerically in more general cases. Let's also note that for any homogenization model defined by an expression of B^{ε} , the macroscopic stiffness $\bar{c}$ is given by:

$$\bar{c} = \left[v_1 c_1 : B^{\varepsilon} + (1 - v_1) c_0 \right] : \left[v_1 B^{\varepsilon} + (1 - v_1) I \right]^{-1}$$

(Eq. 7)

The Mori-Tanaka model (M-T) was proposed by Mori and Tanaka [4] and is such that the strain concentration tensor B^{ε} is equal to $H^{\varepsilon}(I, c_1, c_0)$. Thus the M-T model has the following physical interpretation: each inclusion behaves like an isolated inclusion in the matrix seeing $\langle \varepsilon \rangle_{\omega_0}$ as a far strain field.

From the strain fields in the phases, the stresses can be computed using the material laws assigned to the phases. The material behavior of the phases can be nonlinear and can, amongst other, involved strain-rate or thermal dependencies. These stresses are then averaged in order to compute the macroscopic stresses which thus, if any, reflect the non-linearity and the anisotropy of the composite microstructure at micro-level, as well as the strain-rate or thermal dependencies defined for the phases.

This theory can be extended to composites containing a matrix and inclusions of different shapes, orientations or material properties. The inclusions are classified into *N* phases (*i*) of volume fraction v_i,

$$v_0 + \sum_{i=1}^{N} v_i = 1. \qquad \text{(Eq. 8)}$$

PROCEDURE

DIGIMAT can be linked to LS-DYNA through its user-defined material interface enabling the following two-scale approach: A classical finite element analysis is carried out at macro scale, and for each time/load interval $\left[t_n, t_{n+1} \right]$ and at each element integration point, DIGIMAT is called to perform an homogenization of the composite material under consideration (Figure 2).

Based on the macroscopic strain tensor $\bar{\varepsilon}$ given by LS-DYNA, DIGIMAT computes and returns, amongst other, the macroscopic stress tensor at the end of the time increment. The microstructure is not seen by LS-DYNA but only by DIGIMAT, which considers each integration point as the center of a representative volume element of the composite material.

The material response computed by DIGIMAT will strongly depend on the phases' behavior and the inclusion shape but also on the inclusion orientation.

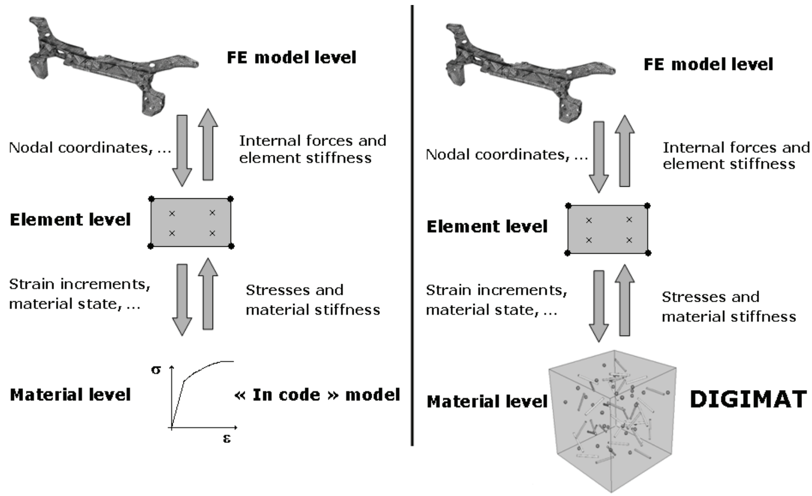

Figure 2: Interaction between DIGIMAT and LS-DYNA. Left: Classical FE procedure – Right: Multi-scale procedure using DIGIMAT as the material modeler

When a part is injected with a polymer reinforced by glass fibers, the fibers' orientation will differ from one point to another. The microstructure of the composite will thus be different for each integration point of the FE model. Interfaces between injection molding software (like Moldflow, Sigmasoft or Moldex3D) and DIGIMAT can also be use jointly with the DIGIMAT – LS-DYNA interface. The predicted microstructure at the end of the molding process (e.g. the orientation of the fibers) can thus be used as an input to DIGIMAT.

Another advantage of using DIGIMAT to simulate composite materials with FE analysis is that, in addition to the macro stress, DIGIMAT will compute stresses and strains in the phases and store it in LS-DYNA history variables. This is very useful, amongst other, in order to apply failure criteria at the microscopic level instead of the macroscopic level.

APPLICATIONS

Impact tests on glass fiber reinforced polymer plates were performed using DIGIMAT coupled to LS-DYNA and can be used, for example, to analyze the sensitivity of the impact properties to the fiber's concentration, orientation and length. Figure 3 shows the initial configuration illustrating the impact tests setup. In this impact analyses, element deletion was based on failure criteria computed at the microscopic scale. Various failure criteria can thus be used (involving stress or strain) and computed, for example, in inclusion's local axes. Figure 4 shows the final distribution of a classical maximum stress failure criterion computed in the axial direction of the fiber's. Figure 5 shows the evolution of the internal energy for three different case of fiber orientation: Fully aligned along an in-plane direction, randomly distributed in the plane of the impacted plate and oriented following the predicted orientation tensors of the injection molding computation.

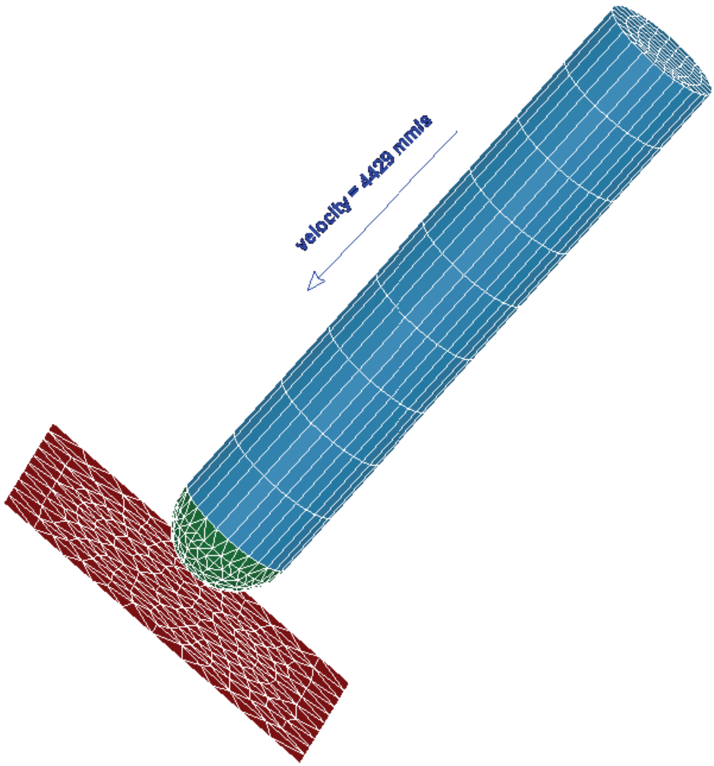

Figure 3: Impact of glass reinforced polymer plate with a falling weight (1m height drop)

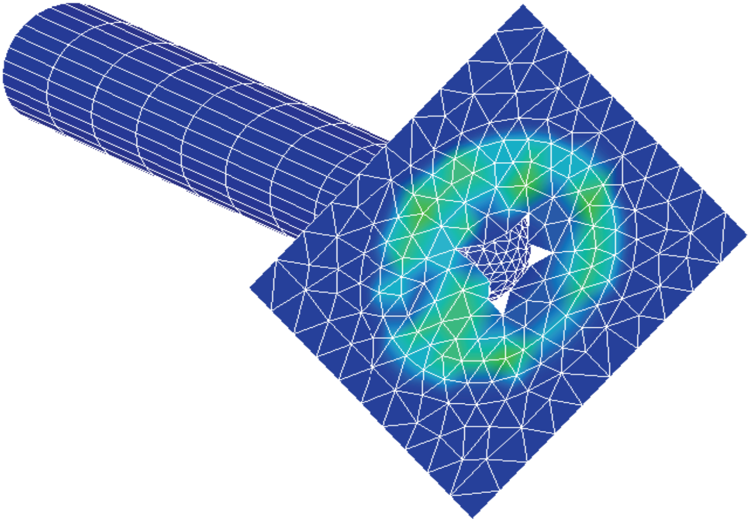

Figure 4: Distribution of failure criterion in glass fiber's.

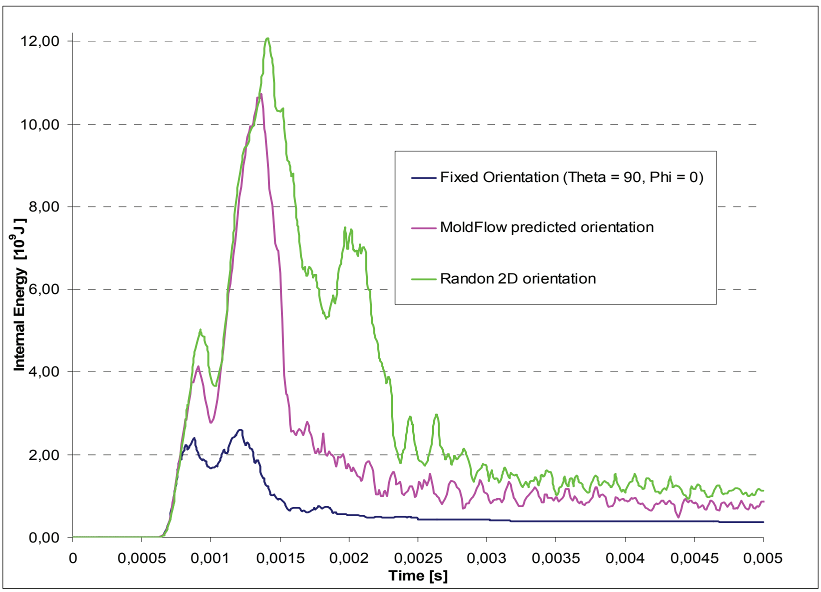

Figure 5: Evolution of internal energies for different cases of glass fiber orientation.

Additional validation and industrial examples will be presented at the conference.

SUMMARY AND CONCLUSIONS

Our homogenization code DIGIMAT was integrated into LS-DYNA through the user-defined material subroutine in order to perform explicit analysis. A two-scale method was used to model the behavior of nonlinear composite structures: a FE model at macro-scale, and at each integration point of the macro FE mesh, the DIGIMAT homogenization module is called. The procedure allows to compute real-world structures made of composite materials within reasonable CPU time and memory usage.

Application to the impact of glass fiber reinforced polymers, using the predicted fiber orientation coming from the injection molding software, was presented.

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