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Accepted Manuscript

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PII: S0266-3538(07)00436-8
DOI: 10.1016/j.compscitech.2007.10.047
Reference: CSTE 3885

To appear in: *Composites Science and Technology*

Received Date: 22 April 2006
Accepted Date: 11 October 2007

Please cite this article as: Jendli, Z., Meraghni, F., Fitoussi, J., Baptiste, D., Multi-scales modelling of dynamic behaviour for discontinuous fibre smc composites, *Composites Science and Technology* (2007), doi: 10.1016/j.compscitech.2007.10.047

MULTI-SCALES MODELLING OF DYNAMIC BEHAVIOUR FOR DISCONTINUOUS FIBRE SMC COMPOSITES

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ABSTRACT

The requirements of passive security, notably in the transport industry, impose to maximize the dissipation of the energy and to minimize the decelerations undergone by a vehicle and thus passengers due to violent shocks (crash). This paper aims at establishing efficient expected answers towards the preoccupations mainly emanating from transport industry. Currently, the behaviour laws implemented in the dynamic explicit schemes (RADIOSS, PAM-CRASH and LS-DYNA) do not integrate sufficiently the physical aspects in the material degradation, mainly the damage process, their kinetics, the variability and especially the heterogeneity of the composite materials microstructure. This paper deals with the development of a multi-scale predictive model coupling specific experimental methodologies and the micromechanical formulation of damage mechanisms in ordre to build constitutive laws for discontinuous fibre reinforced composites materials. The developed micromechanical modelling is based on an experimental methodology conducted over a range of strain rates from quasi static to 250 s^{-1}. The latter has enabled identifying local probabilistic damage criterion formulated through the Weibull's statistical integrating the strain rate effect and describing the progressive interfacial debonding under rapid loading. The developed model has been validated to predict the stiffness reduction and the overall elastic visco-damage behaviour for SMC composite material. The model simulations agree well with high speed tensile tests and confirm that the damage threshold and kinetic in the SMC are mainly strain rate sensitive.

KEYWORDS:

A. Short-fibre composites; B. Interface; C. Damage mechanics; D. High strain rate tensile test.

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1. Introduction

Sheet Moulding Compound (SMC) composites are now increasingly being employed in automotive components as load-structure material and hence are often subject to minor impacts. However, automotive safety requirements, notably those relating to the passengers, become crucial. In addition, recommendations in automotive structural design impose to maximize the dissipation of the energy and to minimize the decelerations undergone by the vehicle passengers during violent shocks (crashworthiness). It is in this context that the analysis and the prediction of mechanical behaviour of materials and structures under dynamic solicitations become very important. Indeed, the overall behaviour analysis, with damage, of composite materials submitted to such solicitations requires theoretical tools and experimental approaches capable to emphasize the effect of the strain rate [1, 2, 3, 4 and 11]. A better understanding of the physical mechanisms of material progressive degradation may contribute to a better formulation of local criteria and then, a better modelling of their effects on the overall dynamic behaviour. With this in mind, in a first time, a multi-scales (macroscopic and microscopic) experimental analysis has been performed on the studied material when subjected to high-speed tensile tests [3, 11]. The main purpose of the developed methodology was to set up a micromechanical model. Three steps have been conducted. Firstly, the quantification of the strain rate effects on the overall behaviour in terms of elastic properties, damage and ultimate characteristics. Secondly, the investigation of the local physical mechanisms involving damage initiation and growth. Thirdly, the use of the experimental results to identify the damage criteria parameter and prediction of the damage evolution.

In the first part of this paper, the experimental approach and results are briefly presented, [3, 11]. The second part of this paper is devoted to the formulation of a multi-scales aimed at predicting constitutive law of a discontinuous randomly oriented fibre reinforced polyester, noted hereafter SMC-R26. The non-linear damaged behaviour has been formulated through for high-speed loading on the basis of a homogenization technique using the Mori and Tanaka schema coupled to a statistical Weibull approach [6, 15]. The developed micromechanical modelling relies upon an experimental methodology performed according to an incremental operating strategy. The damage aspect of the SMC mechanical behaviour is introduced then, on a local scale, through a local probabilistic failure criterion subsequently considered in accordance with the Weibull's statistical function to describe the varying probability of damage [5, 6].

2. Material description

The composite SMC-R (Sheet Moulding Compound Random) consists of an unsaturated polyester resin reinforced by glass fibres and weakly filled with calcium carbonate fillers ($CaCO_3$). Glass fibres have a weight content of 26% and are assembled in bundles in such a way that each one contains approximately 200 fibres. These bundles of fibres are discontinuous and have a constant length (L=25 mm) with a fibre diameter of approximately 15 µm. We define a family of reinforcement as a collection of fibres that exhibit the same volume fraction and orientation. The reinforcement orientation randomly distributed confers to the material a microscopic heterogeneous aspect and an overall transverse isotropic mechanical behaviour. The SMC-R26 plates were prepared of thickness 2.7 mm and were cured at 140 °C with an applied pressure averaging between 7 and 8 MPa for 2 minutes [3]. Moreover, the studied composite microstructure is strongly heterogeneous because of strong local variations of the fibres weight content. Microscopic observations, using scanning electronic microscope, have been performed to investigate the material microstructure and to assess the random fibres orientation. Specimen cartography is then carried out using image analysis to quantify and characterize, at the microscopic scale, the bundles distribution. The fibre orientations are identified by means of SEM micrographs observations performed upon polished surfaces of the specimen. This investigation yields to a quantitative evaluation in estimating fibres orientations (θ_i), weight content (f_i) and aspect ratio (length/diameter), [3, 14 and 15].

3. Mechanical behaviour modelling

The multi-scale models use homogenization techniques to reconstitute the overall behaviour of a representative elementary volume (R.E.V) of a heterogeneous material from the properties of their constituents. In this work, the mean field theory proposed by Mori and Tanaka model [7] was used. The considered formulation gives access (from the microstructure features and the stress (or the strain) applied in the R.E.V.), on the one hand, to the elasticity tensor of the composite and, on the other hand, to the average stress and average strain fields for each constituent; the reinforcement, the matrix and the interface between them.

Indeed, the overall composite behaviour is governed by the mechanical and geometric properties at the local scale. On the other hand, the damage of the composite material is integrated in the proposed model through a progressive density of micro cracks representing the occurring of damage phenomena whose proportion is function of the local stress states estimated for the different phases. Therefore, micro defects are introduced at each increment of the macroscopic stress (Σ_{REV}), and its density is thus evaluated through the calculation of an interface failure probability [5, 10 and 15]. Experimental studies have shown that, for this class of composites materials, the predominant damage mechanism is the fibre-matrix interface failure [3, 14]. The homogenization of the composite material containing fibre, matrix and micro-defects is then achieved through two successive stages (Figure 1). The first one permits to calculate the rigidity tensor of the matrix containing the total micro-defects reached at the considered increment of calculation. Micro-defects are statistically introduced at the local scale through a probabilistic Weibull form fibre-matrix interface failure criterion. The second stage of homogenization consists then in considering the reinforcement in the damaged matrix calculated at the first phase. The approach thus described permits to estimate the stiffness tensor reduction of the composite as a function of the applied rapid loading.

Figure 1: *Two-step homogenization scheme.*

The proposed model can be described therefore in three essential stages:

1) Prediction of the overall (3-D) material stiffness tensor, using the Mori and Tanaka mean field theory coupled to Eshelby's equivalent inclusion model. At this stage, the local stress tensor inside and around inclusions is estimated leading hence to the normal and the tangential component of the stress vector at the interface.

2) Introduction of a local failure criterion (Prediction and quantification of the interfacial cracks) and a damage law.

3) Modelling of the behaviour including the initial anisotropy due to the presence of the reinforcements and its evolution due to damage.

In the next section, the basic equations of the micromechanical model are recalled. These equations give the theoretical framework to estimate overall mechanical behaviour of the composite as well as the local stresses in the fibre-matrix interface. For the sake of completeness, the micromechanical model is briefly described here and more details are given in previous works of the present authors. For a comprehensive introduction to micromechanical and self-consistent models, please refer to the work of Tucker and Liang [18]. These authors have published an excellent review and evaluation of micromechanical stiffness predictions models for unidirectional short fibre composites. Moreover, the reader is also referred to the books by Mura [8] and Nemat-Nasser [19] and other related works [20, 21]. Using the Mori-Tanaka scheme, one predicts the overall three-dimensional effective stiffness tensor of fibrous composite material. Furthermore, average internal stress fields inside and outside fibres and into the matrix [22] and also the stress jump at the interface can be calculated. The reinforcement is assumed to be an ellipsoid inclusion and characterised by a known aspect ratio (length/diameter). The reinforcement inclusion are transformed to equivalent matrix through the application of an eigenstrain using the Eshelby tensor. This enables us to use the expression of the Eshelby tensor clarified by Mura [8] necessary to the determination of the rigidity tensor of the composite. A coupling between the main results expressed by Mori and Tanaka [7], the methods of the equivalent inclusion of Eshelby [9] and the classic techniques of homogenization lead to the expression of the rigidity tensor of the composite (Eq. 1):

$$C^{comp} = C^m \left[I + f < Q > \left(I + f < (S - I)Q > \right)^{-1} \right]^{-1} \qquad (1)$$

Where, f, represents the reinforcement volume fraction, <Q>, the average value of the 'pseudo-tensors' of localisation, Q^i, defined for each reinforcement family as (Eq. 2) :

$$Q^i = ((C^m - C^i)(S^i - I) - C^i)^{-1}(C^i - C^m) \qquad (2)$$

In these expressions, S^i is the Eshelby tensor of the *i*th reinforcement family, which depends on the matrix mechanical characteristics and on the reinforcement geometry and orientation.

C^m and C^i are respectively the stiffness of the matrix and of the *i*th reinforcement family. These tensors are all expressed in the macroscopic principal axes of the composite plate.

The behaviour of the organic composite materials is generally an isotropic elastic behaviour or damageable elasto-plastic. For this material [5, 10], the main source of non-linearity comes from the interface fibre-matrix damage. The matrix remains isotropic elastic. It is therefore necessary to calculate the stresses on all points of the interface. For a macroscopic stress, Σ, the tensor of the average stresses inside a fibre oriented in the θ_i direction is given by the following equation (Eq. 3):

$$\sigma^{i} = C^{m}(I + (S^{i} - I)Q^{i})(I + f < (S - I)Q >)C^{m^{-1}}\Sigma \qquad (3)$$

The interfacial stresses can be calculated while using the continuity condition of the normal stress across the interface. The normal and tangent stresses for each point of the interface, by it's normal '$\vec{n}$' are gotten by simple projection of the stress tensor axes (Eq. 4), (Figure 2).

Figure 2: *Projection of the stress tensor (normal, σ and tangent, τ interface stresses).*

$$\sigma_n = \vec{\boldsymbol{T}} \cdot \vec{\boldsymbol{n}} \qquad \tau^{i} = \sqrt{\left\|\vec{T}\right\| - (\sigma_n)^2} \qquad (4)$$
$$\vec{\boldsymbol{T}} = \sigma^{i} \cdot \vec{\boldsymbol{n}}$$

4. Experimental approach and tests data

An experimental methodology devoted to the micro and macroscopic characterisation of damage and the overall mechanical behaviour of SMC-R26 subjected to high-speed loadings has been developed and optimized [3, 11 and 12]. The experimental procedure has been optimised in an attempt to isolate the inherent inertial disturbances attributed to the test system. The optimisation aims at minimizing the amplitude of measurement perturbations in order to give rise to homogeneous stress/strain fields and constant strain rate within the tested specimen. The developed approach has been applied at strain rates up to 200 s^{-1}. Experimental results obtained for high-speed tensile tests are summarized and reported in the Figure 3. As expected, these results show a large strain rate sensitivity notably during the damage accumulation stages prior the macroscopic failure of the specimen. The strain-rate sensitivity arises through an increase of the damage characteristics in terms of damage threshold and ultimate stress level (failure). It must be pointed out that for the studied composites material (SMC-R26), the elastic stage of the stress-strain curve seems to be insensitive to the strain-rate. Furthermore, the identification of the multi-scales model parameters requires an experimental analysis of the damage evolution at the microscopic scale of the material. Interrupted rapid tensile tests, originally proposed by Lataillade [13], have been numerically optimized [11] and then performed according to an incremental operating strategy. These tests are analysed at the two material scales: At the macroscopic scale, enabling hence the characterisation of the stages of the dynamic behaviour and the progressive stiffness reduction of the SMC-R26. The second scale is the microscopic scale using a SEM for microscopic observations and analysis. The evolution of a microscopic damage parameter, d_{micro}, (Figure 4-a), defined as the percentage of fibres whose the interface are debonded increasing thus the microdefects density. This damage mechanism is then experimentally quantified by micrographic analysis and correlated to a macroscopic damage parameter D_{macro}, (Figure 4-b) through the developed micromechanical model. The D_{macro} is defined using the well-known damage mechanics theory [16, 17] and expressed such as (Eq. 5):

$$D = 1 - \frac{E^D}{E^0} \qquad (5)$$

E^0 and E^D, are respectively the Young's modulus of virgin and damaged material. The latter is estimated at the elastic unloading when interrupting the tensile test. This permits obtaining, for each strain rate, the evolution of the material degradation (expressed as a stiffness reduction) as a function of the strain level (Figure 4-b). It should be noted here that for the studied range of strain rates, the performed rapid tensile tests showed, on the one hand, that the behaviour of the material is bilinear. On the other hand that, independently of the strain rate, the main damage phenomenon remains the fibre-matrix interface failure (for more details, please see [11 and 14]). One can observe in Figures 3 and 4-b, that the interfacial damage threshold is more delayed with the increase of the strain-rate. In addition, for the elastic stage of the overall response, one notices that the limit of elasticity increases with the strain rate. Otherwise, one can note (Figure 4-a) that the interfacial damage rate is less important when the loading speed increases. One can conclude therefore that the behaviour of the material is mainly governed by the damage viscosity [15], see also [11, 14] for a complete description of the strain rate effects on the interface failure evolution.

Figure 3 : *Effect of strain rate in the tensile behaviour of SMC R26.*

Figure 4 : *Evolution of the damage quantified,* (a) *at microscopic scale (dmicro) and* (b) *macroscopic scale (Dmacro), in the SMC-R26 composite according to the strain.*

5. Damage and failure criterion

In order to integrate and understand the damage effects on the macroscopic behaviour, a local interfacial failure criterion is statically introduced, at the reinforcements scale, in the Mori and Tanaka model. The interface failure being produced by a combination of the local normal and the local shear stresses, the loading state is calculated for each point of the interface. An elliptic failure criterion is then introduced. The approach being statistical [5, 6 and 15], the probability to get an interfacial rupture is calculated for each point of the interface, and for each family of orientation by the following expression (Eq. 6):

$$P_r(\sigma,\tau,m) = 1 - \exp(-[\left(\frac{\sigma}{\sigma_0}\right)^2 + \left(\frac{\tau}{\tau_0}\right)^2]^m) \quad , (\sigma_0, \tau_0, m) = f(\dot{\varepsilon}) \qquad (6)$$

Where σ and τ are respectively the normal and shear stresses, in the considered point, of the interface. (σ_0, τ_0) correspond to the resistance of the fiber-matrix interface. (m) is the damage parameter discribing statically the damage kinetic of the interface (Figure 4-a). The parameters (σ_0, τ_0, m) are function of the strain rate (Figure 6). The values of these parameters are identified for every strain rate by an inverse method using extensively the experimental results described in the previous paragraph. Once the interface failure probability for each orientation family is calculated. The damage of the composite material is integrated through the introduction of a density of heterogeneities having a null stiffness tensor simulating the micro cracks presence due to the interfacial damage. Their geometry is ellipsoidal with a dimension following a main axis is the order of 2 to 3µ (corresponding to the average opening of the cracks observed in the MEB). The quantities of introduced micro cracks at each increment of stress are directly related to interface failure probabilities calculated for each family of orientation. The quantities of micro cracks are then evaluated for each increment of the macroscopic stress (Σ_{VER}). Besides, the fibres weight content is estimated at the end of the step calculation. Thus, when an inclusion having a given orientation is partially damaged (debonded), the orientation family according this angle will be considered for the next steps as a reinforcement family with a less important fibre volume fraction (Figure 5). The homogenization of the composite material containing fibre, matrix and micro defects is then achieved in two successive stages as described previously in above.

Figure 5: *Integration of the damage in the model*

(a) Bundle of fibre partially damaged 'θ'oriented,

(b)Equivalent system considered in the proposed model.

6. Identification - results and discussion

The first stage consists in the identification of the local failure criterion parameters of the fibre-matrix interface. The latter is conducted using an inverse method. Indeed, for a known, σ_0, τ_0, m, parameter, the model can predict the evolution of the densities, d_{micro}, of cracks created at the fiber-matrix interface according to the imposed strain [15]. The defects density has been measured directly on the composite micrographs successively loaded according to interrupted tests methodology (see Figure 4-a). For each studied strain rate, a set of parameters (Figure 6) is identified on the basis of the experimental results through a least-square minimization using a Levenberg – Marquardt algorithm [23, 24].

Figure 6: *Evolution of σ_0, τ_0 and m vs. strain rate (from 2.10^{-4} to 350 s^{-1}).*

On the Figure 7, is given an example of the identification result. Once the criterion identified as a function of the strain rate, the modelling procedure, described in the previous paragraphs, enables simulating the stress-strain curves for different strain rates [15]. The Figure 8 shows simulated stress-strain curves compared to those obtained experimentally for two different strain rates. One can note a good correlation between them for different strain rates. The model identified at the microscopic scale is validated at the macroscopic scale for tensile tests.

Figure 7: *Tests-model correlation:*

Microscopic damage evolution exploited to identification of the multi-scales model parameters $\dot{\varepsilon} = 8\ s^{-1}$.

Figure 8: *Tests- modelling correlation :*

Examples of macroscopic stress-strain curves for two strain rates 22 and 150 s^{-1}.

The developed multi scale model allows predicting 3-D stiffness reduction brought about by the high-speed loading achieved at different crosshead velocities (Figure 9). Furthermore, the micromechanical model is used as a "virtual multi-axial testing" to determine a macroscopic damage criterion evolution for a SMC composite subjected to different 3-D loading paths: proportional and non proportional. A macroscopic three dimensional viscodamage law for an anisotropic material is established taking into account the anisotropy evolution due to the multiaxial loading. The determination of the macroscopic criterion relies hence upon experimental data obtained with only a tensile test analysed at a microscale.

Figure 9: *Predicted stiffness reduction (E_{11}, E_{33} and G_{13})*

brought about by damage at three strain rates (2.10^{-4},20 and 250 s^{-1}).

7. Conclusions and perspectives

The experimental approach has allowed establishing for the SMC-R26 composite that the effect of the strain rate conditions mainly the threshold and the kinetics of deterioration notably to the level of the fibre-matrix interface. In other words, the interface decohesion is mainly sensitive to the strain rate. This damage mode would lead then to an elastic visco-damageable behaviour for this typical composite material. These experimental observations were helpful guidelines for the developed modelling. Indeed, the effect of the strain rate on the interface failure is achieved through the proposition of a statistical local criterion sensitive to the strain rate in term of threshold and kinetic. The identification is achieved on a local scale and the model is validated on a macroscopic scale based on the rapid traction results [15]. Thus, the work presented in this article is an evolution toward a dynamic version of models developed in static on these materials. The gotten results are in very good adequacy with the experience.

The present work constitutes a contribution to the prediction of the macroscopic behaviour of discontinuous fibre composite subject to dynamic loading. Actually, these approaches may be helpful to setup behaviour data, which are used in the dynamic FE codes. It will be able to be introduced as law user or to identify a macroscopic constitutive law. Furthermore, the micromechanical model is able to describe directional stiffness degradation under general loading path. The proposed multi-scale model would be applied as an inverse approach for optimising the material microstructure of composite choc components on the basis of design requirements.

8. References

1. Okoli OI. The effects of strain rate and failure modes on the failure energy of fibre reinforced composites. Composite Structure 2001; 54: 299-303.
2. Dear JP, Brown S.A. Impact damage in reinforced polymeric materials. Composites Part A: Applied Science & Manufacturing, 2003; 34: 411-420.
3. Jendli Z., Meraghni F., Fitoussi J., Baptiste D. Micromechanical analysis of strain rate effect on damage evolution in Sheet Molding Compound composites. Composites Part A: Applied Science & Manufacturing, 2004; 35: 779-785
4. Lee H.K and Simunovic. S. A damage mechanics model of crack-weakened, chopped fiber composites under impact loading, Composites Part B: Engineering 2002; 33: 25-34.
5. Fitoussi J., Guo G. and Baptiste. D. A statistical micromechanical model of anisotropic damage for S.M.C. composites, Composites Science and Technology. 1998; 58 (5): 759-763.
6. Meraghni F., Desrumaux F., Benzeggagh ML. Implementation of a constitutive micromechanical model for damage analysis in glass mat reinforced composites structures. Composites Science and Technology 2002; 62: 2087-2097.
7. Tanaka K. and Mori T. The hardening of crystals by non-deforming particles and fibers. Acta mettallurgica 1970; 18: 931-941.
8. Mura T. Micromechanics of defects in solids. Second revised edition1987. Martinus Nijhoff Publishers, la Hague.
9. Eshelby, J.D. The elastic field outside an ellipsoidal inclusion. Proceeding of royal society London Series A. 1959; 252: 561 - 569.
10. Fitoussi J., Bourgeois N., Guo G., Baptiste. D. Prediction of the Anisotropic Damaged Behavior of Composite Materials: Introduction of Multi-Local Failure Criteria in a Micro-Macro Relationship. Computational materials science 1996; 5: 87-100.
11. Fitoussi J., Meraghni F., Jendli Z., Hug G. and Baptiste D. Experimental methodology for high strain-rates tensile behaviour analysis of polymer matrix composites. Composites Science and Technology 2005 ; 65 (14) : 2174-2188.
12. Jendli Z., Fitoussi J., Meraghni F., Baptiste D. Analyse micromécanique de l'effet de la vitesse de déformation sur l'endommagement de matériaux composites à fibres courtes SMC-R. Compte rendu des JNC13. 2003; 995-1004.
13. Lataillade J-L., Delaet M., Collombert F., Wolff C. Effects of the intralaminar shear-loading rate on the damage of multi-ply composites. Int. J. Impact Engng 1996; 18(6): 679-699.

14. Zouhaier Jendli, Joseph Fitoussi, Fodil Meraghni, Didier Baptiste. Anisotropic strain rate effects on the fibre-matrix interface decohesion in Sheet Moulding Compound composites. Composites Sciences and Technology. 2005; 65 (3-4) : 387-393.
15. Jendli Z. Analyse et Modélisation Multi-échelles du Comportement Mécanique sous Sollicitations Rapides de Composites SMC, Thèse de Doctorat, Ecole Nationale Supérieure d'Arts et Métiers, ENSAM – Paris, 8 juillet 2005
16. Krajcinovic D., Mastilovic S. Some fundamental issues of damage mechanics. Mechanics of Materials 1995; 21: 217-230.
17. Krajcinovic D. Selection of damage parameter – Art or science? Mechanics of Materials 1998; 28: 165-179.
18. Tucker CL and Liang E. Stiffness predictions for unidirectional short-fibre composites: Review and evaluation. Composites science and technology 1999; 59: 655-671.
19. Nemat–Nasser S and Hori M. Micromechanics : Overall properties of heterogeneous materials. 1993 North-Holland series in applied mathematics and mechanics. ISBN 0-444-89881-6.
20. Benveniste Y. A new approach to the application of Mori-Tanaka's theory. Mechanics of materials 1993; 6: 147-157.
21. Chen T, Dvorak GJ and Benveniste Y. Mori-Tanaka estimates of the overall elastic moduli of certain composite materials. Journal of applied mechanics 1992; 59: 539-546.
22. Mori T and Tanaka K. Average stress in matrix and average elastic energy of materials with misfitting inclusion. Acta. Metall. 1973; 21: 571-574.
23. Levenberg K. A method for the solution of certain nonlinear problems in least squares. Questions of Applied Mathematics. 1944 ; 2: 164-168.
24. Marquardt D.W. An algorithm for least squares estimation of nonlinear parameters. J. Soc. Ind. Apll. Math. 1963; 11: 431-441.

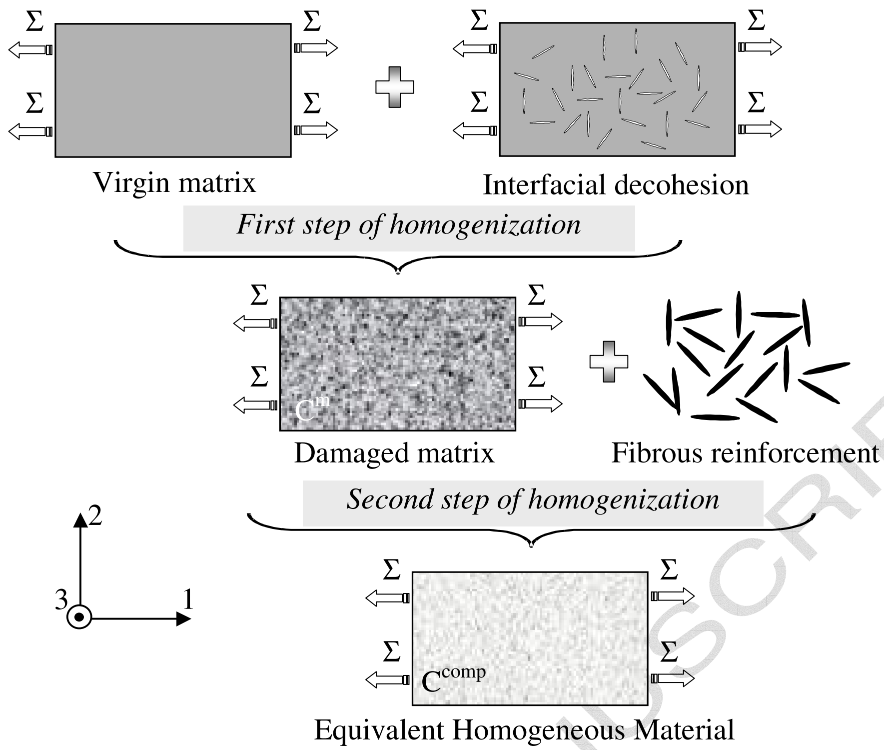


Figure 1: *Two-step homogenization scheme.*

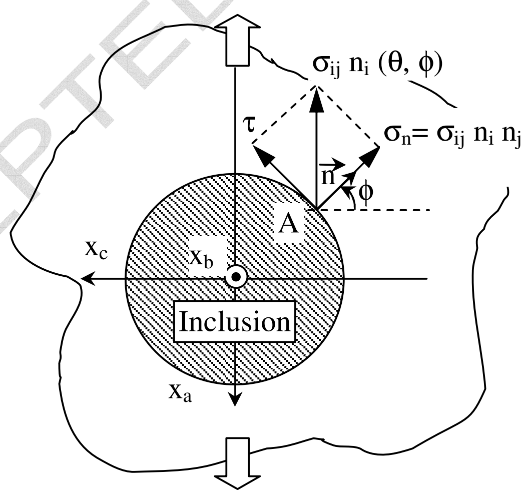
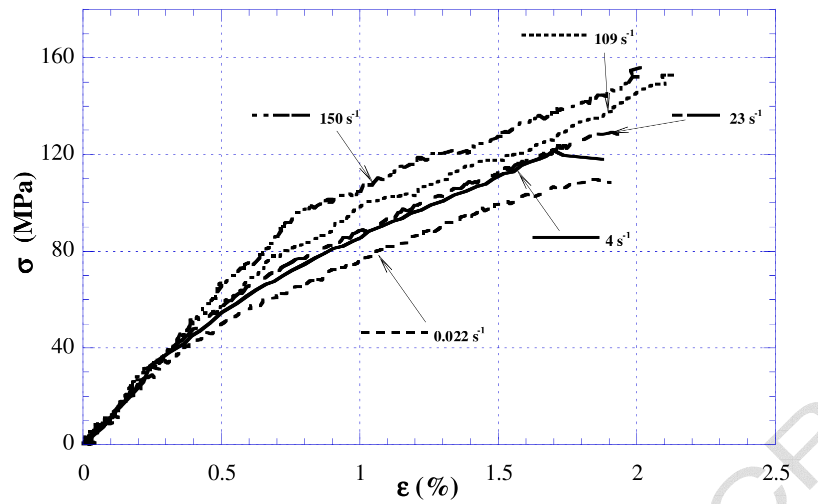


Figure 2: *Projection of the stress tensor (normal, σ and tangent, τ interface stresses).*



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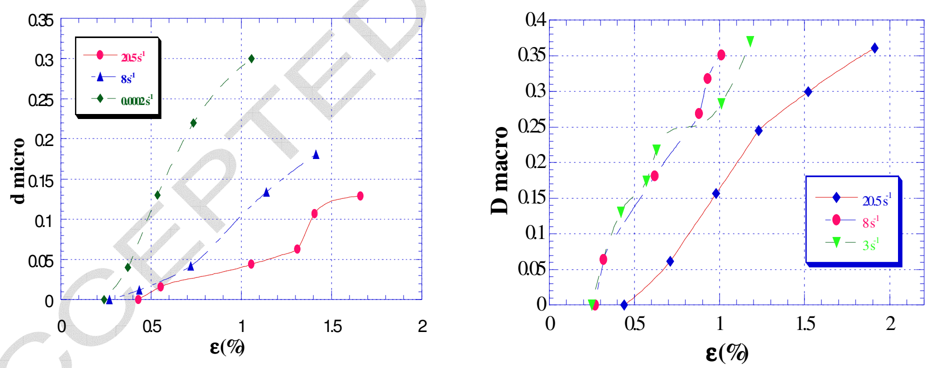

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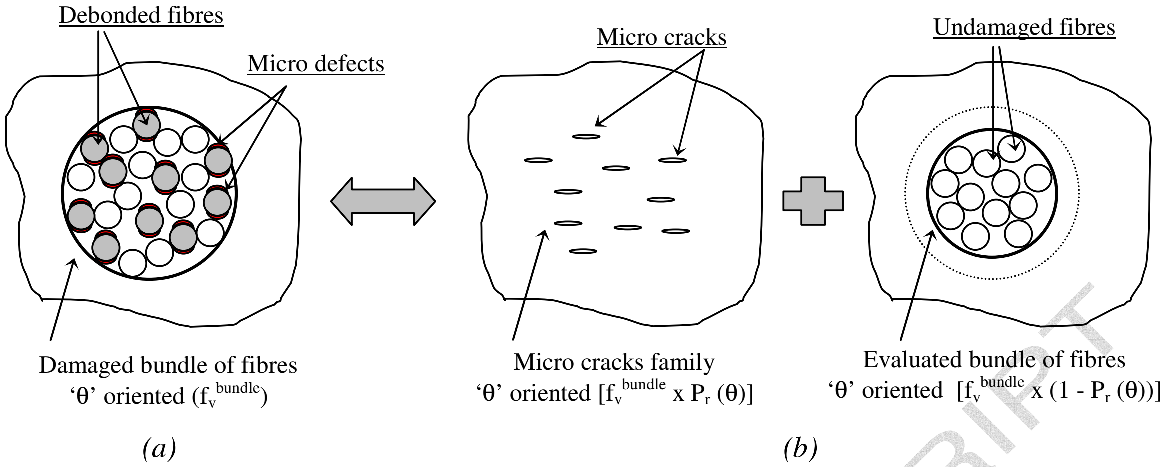

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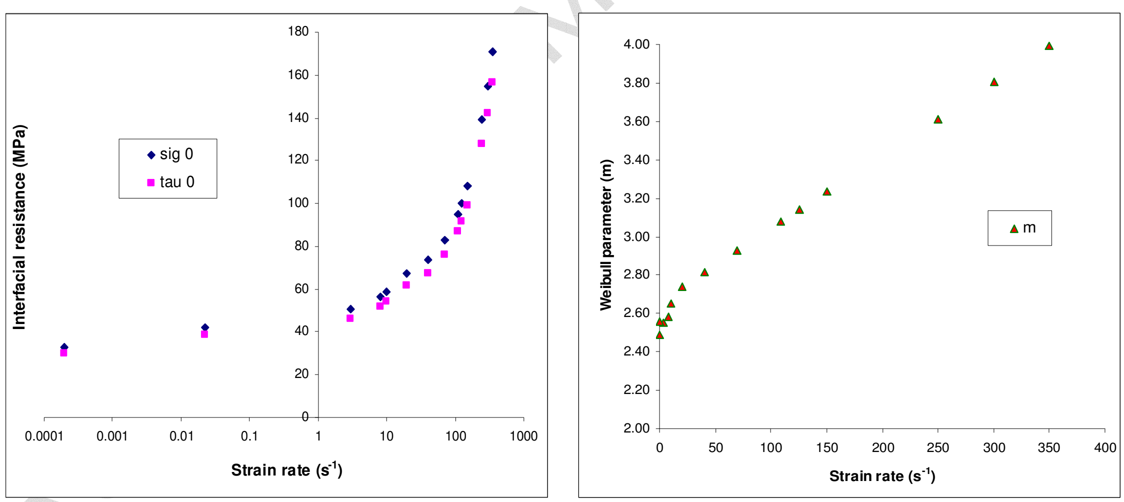
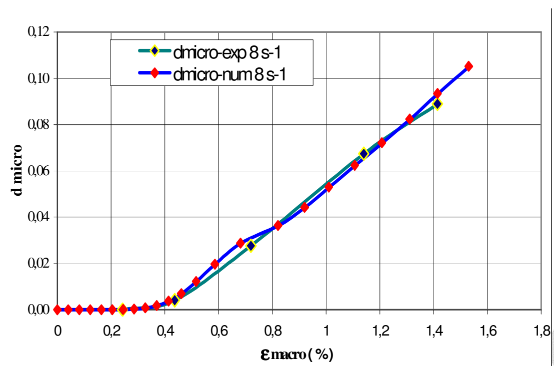


Figure 6: *Evolution of σ_0, τ_0 and m vs. strain rate (from 2.10^{-4} to 350 s^{-1}).*



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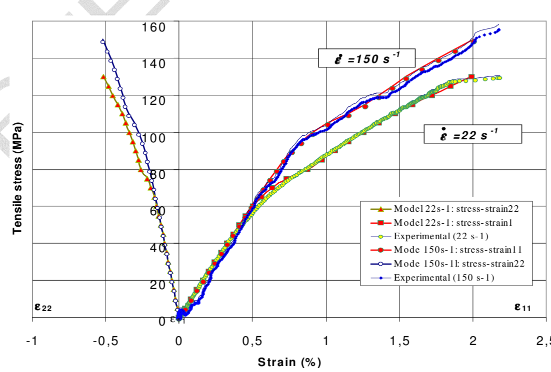

Figure 8: *Tests- modelling correlation:*

Examples of macroscopic stress-strain curves for two strain rates 22 and 150s^{-1}.

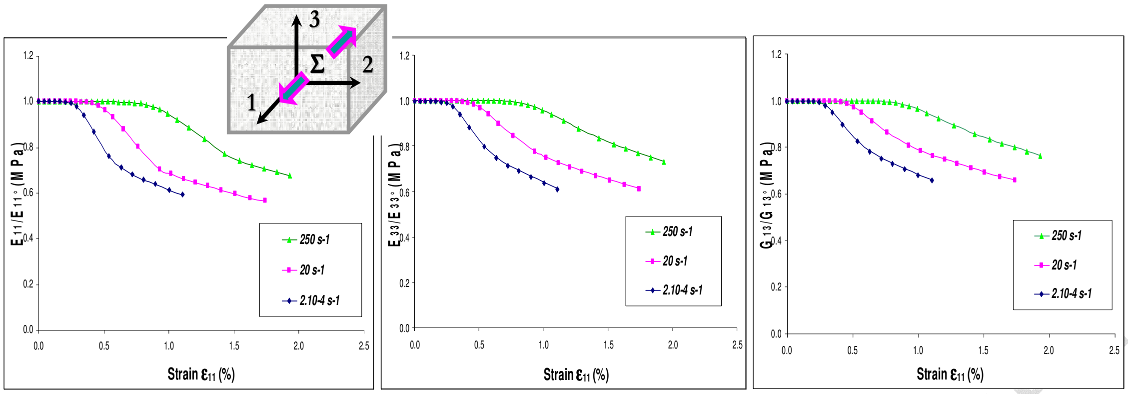

Figure 9: *Predicted stiffness reduction (E_{11}, E_{33} and G_{13})*

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