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Explicit multiscale modelling of impact damage on laminated composites – Part I: Validation of the micromechanical model

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ABSTRACT

This work presents the development and verification of a multiscale methodology applicable for modelling of impact damage in laminated composite structures. The methodology employs the High Fidelity Generalized Method of Cells (HFGMC) micromechanical model for the prediction of local stress/strain fields within the unidirectional composite material. The micromechanical model has been coupled with Abaqus/Explicit, where the structural scale computations have been performed.

The methodology utilises the Mixed Mode Continuum Damage Mechanics theory (MMCDM) as to model damage within the composite microstructure. Validation and application of the multiscale methodology have been presented in two separate papers. Part I presents an overview of the micromechanical model and validation of the micromechanical damage model, whereas the multiscale analyses have been demonstrated in Part II of the paper.

The micromechanical damage model parameters have been determined by correlation with available experimental data of the nonlinear behaviour of the homogenised composite material at in-plane shear and transverse compressive loading. The obtained results demonstrate the ability of the micromechanical approach to model accurately the failure modes of the composite material, as well as the nonlinear behaviour of the composite plies at the in-plane shear and transverse compressive loading.

1. Introduction

The reliability of numerical failure prediction methods can be increased by modelling of the damage processes at the microstructural level since the failure modes of composite materials are an immediate result of processes within the heterogeneous material. Application of the micromechanical theories at structural-scale problems has been enabled by employing multiscale principles, as shown schematically in Fig. 1 for the methodology described in this paper.

The multiscale approach separates the analysed problem on two length scales – the macro-scale, which solves the problem at the engineering level usually employing the finite element method, and the micro-scale, at which the stress and strain fields within the microstructure have been determined. An advantage of the multiscale damage modelling approach using micromechanical models is that the processes within the unit cell of the composite material are explicitly taken into account in the analysis of composite structures. Consequently, modelling of effects that determine homogenised mechanical properties of fibre reinforced composite materials, e.g. the unit cell morphology and fibre/matrix interphase effects, has been enabled.

A very broad range of analytical, semi-analytical and numerical micromechanical models has been developed throughout the literature with the focus on modelling of the homogenised composite elasticity properties based on the properties and microstructural arrangements of the constituents. However, the computational effectiveness has been considered an essential aspect in the conceptual stage of the methodology development since the micromechanical scale solves the constitutive relations for the structural level FE explicit analyses. Therefore, the methodology has been based on advanced semi-analytical micromechanical models. Due to the wide range of applications in the literature and the favourable computational properties, the reformulated HFGMC model has been selected as the micromechanical model in the developed methodology.

Compared to the preceding Method of Cells-based micromechanical models (MOC, [1]), as for example the Generalized Method of Cells (GMC, [2]), HFGMC employs a second-order Legendre type polynomial to approximate the displacement field within the subcell. This feature leads to fundamental differences between

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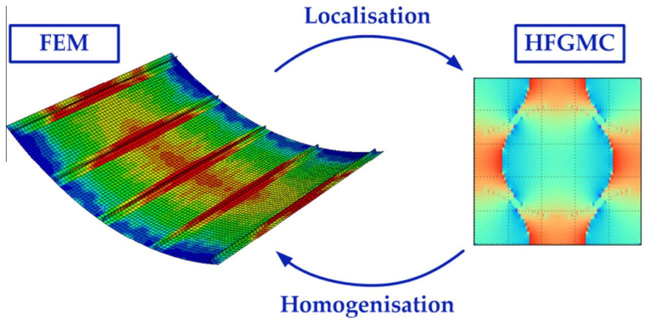

Fig. 1. Two-scale methodology applied in this work.

the HFGMC and GMC, although they share the same unit cell discretization. Comparison of the results and computational aspects of the GMC and HFGMC micromechanical analyses has been provided in e.g. [3,4]. Despite the described GMC shortcomings, it has been employed extensively in the literature, especially in the multiscale framework where the computational properties of the model are exploited.

Ply-level failure theories which account for damage effects prior to complete ply failure performed better in the failure theory evaluation, as concluded in the aftermath of the WWFE, after [7]. These microdamage effects cause nonlinearities in the in-plane shear and transverse compressive constitutive behaviour of the composite plies, where the matrix properties govern the homogenised material response. Progressive damage mechanics principles need also to be included in the micromechanical theories as to improve the prediction of failure onset and complete failure of the composite material, as shown by the results of the early applications of failure theories in micromechanical models.

Micromechanical damage has been modelled by the instantaneous degradation of subcell mechanical properties in the first applications of MOC-based micromechanical models for prediction of composite laminate failure. Results of these early applications have been published in e.g. [5,6], where the GMC micromechanical model has been used for this purpose. In these approaches, initiation of micromechanical damage has been predicted employing failure criteria at the subcell level, considering the different homogenised stress states at which damage has been initiated in the individual constituents. Consequently, matrix failure has been predicted using e.g. the Tsai–Wu and Tsai–Hill criteria whereas the maximal stress and strain in fibre direction criteria have been employed for the fibre subcells.

In these early applications, damage has been modelled by degradation of mechanical properties to very low values (0.01% of the undamaged values) for subcells that reach the failure state employing the relevant failure theory. The subsequent application of the homogenisation procedure over the Representative Unit Cell (RUC), which includes the completely degraded subcells, results in progressive degradation of the composite mechanical properties. However, the obtained effect of progressive degradation on the homogenised properties has not been sufficient as to enable modelling of the pronounced nonlinear behaviour of epoxy-based composite plies at in-plane shear and transverse compression prior to complete failure of the material, as discussed in [7]. Therefore, the microdamage mechanisms have been included into the developed multiscale damage modelling approach using the Mixed-Mode Continuum Damage Mechanics (MMCDM) progressive degradation model, after [7].

Conclusions drawn from these studies highlighted the importance of the application of the more refined constituent level damage modelling approaches at the micromechanical level. Evaluation of several micromechanical failure initiation criteria has been performed in [8] as a preface to the presented research. In this reference, the failure initiation theories have been validated and compared against each other. The assessment consisted of the comparison of failure initiation curves in the homogenised ply stress space, at which the HFGMC model predicts failure onset. Furthermore, the distribution of the failure initiation criteria in the composite RUC at the failure onset, as predicted by the assessed failure theories, has been presented. This work focuses on the validation of the MMCDM model for modelling of damage processes in the epoxy-based composite plies.

2. Micromechanical model

The governing equations of the HFGMC model have been derived in [9], whereas the reformulation of the theory, which has been employed throughout this research, has been introduced in [10]. Additionally, the theoretical background and the form of the HFGMC system of equations, which has been utilised in this research, are summarised in [8]. Therefore, only the most significant relations have been provided in this work as to enhance the completeness of the text.

The unit cell discretization scheme of the reformulated HFGMC model is shown in Fig. 2. The model for the unidirectional fibre reinforced material is based on the assumption that x_1 is aligned with the fibre direction, x_2 lies in the ply plane and x_3 is perpendicular to the ply plane. Therefore, the coordinate system used for the HFGMC model corresponds to the material coordinate system of the composite ply. The unit cell, having dimensions $l \times h$, is discretized into $N_\beta \times N_\gamma$ rectangular subcells while the constitutive behaviour of the individual subcells is governed by the elasticity tensor $C_{ijkl}^{(\beta,\gamma)}$.

The final aim of micromechanical theories is to determine the strain concentration tensors $A_{ijkl}^{(\beta,\gamma)}$ which relate the microstructural strain field $\varepsilon_{ij}^{(\beta,\gamma)}$ based on the applied homogenised strain state $\bar{\varepsilon}_{kl}$

$$\varepsilon_{ij}^{(\beta,\gamma)} = A_{ijkl}^{(\beta,\gamma)} \bar{\varepsilon}_{kl}. \tag{1}$$

The HFGMC theory assumes the displacement field within the subcells in the form

$$u_i^{(\beta,\gamma)} = \bar{\varepsilon}_{ij} x_j + u_i'^{(\beta,\gamma)},\ i = 1,2,3, \tag{2}$$

where the first term on the right side represents the contribution of the homogenised (averaged) strain, while u_i' represents the fluctuating displacement field within the (β,γ) subcell. This displacement component has been approximated using a second-order Legendre-type polynomial expansion in the local subcell coordinates $(\bar{y}_2, \bar{y}_3)$

$$u'^{(\beta,\gamma)} = W_{i(00)}^{(\beta,\gamma)} + \bar{y}_2^{(\beta)} W_{i(10)}^{(\beta,\gamma)} + \bar{y}_3^{(\gamma)} W_{i(01)}^{(\beta,\gamma)} + \frac{1}{2}\left(3\bar{y}_2^{(\beta)2} - \frac{h_\beta^2}{4}\right) W_{i(20)}^{(\beta,\gamma)} + \frac{1}{2}\left(3\bar{y}_3^{(\gamma)2} - \frac{l_\gamma^2}{4}\right) W_{i(02)}^{(\beta,\gamma)},\ i = 1,\ 2,\ 3, \tag{3}$$

after [9]. The W variables in Eq. (3) are microvariables that define the fluctuating displacement field within each subcell and have to be determined to calculate the strain field within the unit cell. Derivation of the subcell displacement expansion, as defined in Eqs. (2) and (3), with respect to the subcell local coordinates using

$$\varepsilon_{ij}^{(\beta,\gamma)} = \bar{\varepsilon}_{ij} + \frac{1}{2}\left(\frac{\partial u_i^{(\beta,\gamma)}}{\partial \bar{y}_j^{(\beta,\gamma)}} + \frac{\partial u_j^{(\beta,\gamma)}}{\partial \bar{y}_i^{(\beta,\gamma)}}\right) \tag{4}$$

resolves the microscopic strain field.

The distinctive feature of the reformulated HFGMC is the introduction of the local and global stiffness matrices. The local stiffness