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Micromechanical damage modelling using a two-scale method for laminated composite structures

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ABSTRACT

Failure mechanisms of fibre reinforced composite structures are closely related to processes within the heterogeneous material. In order to include these processes in numerical simulations a micromechanical model needs to be coupled to the finite element solution. This two-scale framework has in the current work been achieved using the reformulated High Fidelity Generalized Method of Cells (HFGMC) micromechanical model and the finite element code Abaqus/Explicit. The two-scale approach enables calculation of the stress field within the unit cell, based on the constitutive behaviour of each subcell and the unit cell morphology. As the stress distribution is determined for the representative unit cells, calculation of failure criteria and constitutive response of the composite are performed at the micro-level. Damage effects are also being modelled on the micromechanical level. Failure initiation has been predicted using three micromechanical failure criteria found in the literature – the 3D Tsai–Hill model, the MultiContinuum Theory model and the 3D Hashin type strain based failure criteria. Degradation of mechanical properties of the composite material has been introduced to the model using the damage model described in the work of Bednarcyk et al. [19]. The damage model relies on the 3D Hashin type strain based failure criteria and shows good agreement with experimental results.

1. Introduction

Results of the World Wide Failure Exercise (WWFE) [1,2] revealed complexity of failure and damage prediction in laminated composite structures for wide ranges of loading conditions. The aim of composite engineering is to employ composite materials to a wider range of primary structural items of lightweight structures. In the aerospace industry, composite materials have long been used only for secondary structural items. An example of the novel approach to composite structures application is the A400M transport aircraft, in which the main wing spars, as the primary load carrying items of the wing structure, are made of CFRP material [3].

The complexity of the failure prediction in composite structures arises from the heterogeneous microstructure of composite materials. As a consequence, failure processes of composite structures are governed by microstructural phenomena. These effects at the micro-scale are modelled using micromechanical principles. Reviews and comparisons of most widely used micromechanical theories are provided e.g. in [4,5]. The micromechanical model applied in this work is the reformulated HFGMC model [6]. The model belongs to a group of micromechanical models developed from the Method of Cells theory (MOC) [7,8].

A current approach in numerical analysis of heterogeneous materials is the multiscale approach. The separation of the analysed problem into several length scales enables application of micromechanical models in the analysis of large scale engineering problems. The multiscale methodology has been employed in this work as well. The problem of failure and damage prediction has been analyzed at two different length scales in the current research. Large-scale analyses have been performed using Abaqus/Explicit.

The micromechanical model calculates the stress and strain field within the heterogeneous microstructure. As the stress and strain states are known within the heterogeneous microstructure, failure initiation and damage progression models are applied at the micro-structural level. This work covers results of the initial research phase, in which the main interest has been in the evaluation of micromechanical failure theories. Failure theory comparison has been achieved using two approaches. The first approach employs a stand-alone application of the micromechanical model and creates failure curves in the macro-scale stress space. Application of micromechanical failure theories on a benchmark large-scale numerical model is the second approach employed in this work.

2. Micromechanical model

Despite the fact that the MOC theory dates back to the 1980s, development of models based on the MOC is still very attractive,

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especially due to higher computational efficiency (compared to e.g. finite element micro-models) and versatility of the models. Discretization of material heterogeneity in micromechanical models based on the MOC has been achieved using subcells which can have different mechanical properties.

The unidirectional composite material has been discretized by only four subcells in the original MOC theory (one fibre subcell and three matrix subcells). Despite the rough discretization, these micromechanical models have been used to solve complex problems such as inelasticity in the Metal Matrix Composites (MMC) and fibre/matrix debonding [7,8].

Advances in computational capabilities led to extension of the MOC model into the Generalized Method of Cells (GMC) [9]. The GMC model employs the same governing equations as the MOC, but unit cell discretization is now accomplished using arbitrary number of subcells. Consequently, modelling of complex unit cell shapes has been made possible. The GMC model has in recent publication been used as a micro-model in multiscale analyses as for example [10–13].

There are several drawbacks which limit the applicability of the GMC model in composite damage prediction analyses, as addressed in [14]. The most important is the lack of "normal-shear coupling". This term indicates that application of macroscopic normal strains/stresses to GMC models produces only normal subcell strains/stresses although each subcell is isotropic, transversely orthotropic or orthotropic. Accordingly, macroscopic shear strains/stresses produce only averaged shear subcell strains/stresses. As stated in [6], this deficiency can potentially produce very inaccurate results in the presence of cracks, disbonds or porosities.

This important drawback has been solved by introduction of a second order displacement approximation in the High Fidelity Generalized Method of Cells as explained in [15,16]. The HFGMC uses a second order Legendre type polynomial to approximate the displacement field within the subcell, leading to fundamental differences between the HFGMC and GMC. Comparison of GMC and HFGMC micromechanical analyses can be found for example in [14,17]. Versatility of the HFGMC has been demonstrated in various applications, e.g. fibre/matrix debonding [14], matrix plasticity [15], shape memory alloys [18] and damage in composites [19–21]. The HFGMC has also been used in the multiscale framework, e.g. in [20]. Recent developments include parametric implementations of the HFGMC [22,23] and theories which study localisation effects in composite materials [24,25].

The reformulated HFGMC model, introduced in [6], has been employed in this methodology. This model has been later renamed as Finite Volume Direct Averaging Micromechanics (FVDAM) [26]. The main improvement of the reformulation, in comparison with the original HFGMC, is that it departs from the concept of Generic Cells, reducing the final system of equations by 60%, thereby significantly increasing computational effectiveness, after [6]. Despite the reformulation, basic features of the model such as fundamental theory, boundary conditions and unit cell discretization remain the same as in the original HFGMC.

Micromechanical models developed from the Method of Cells are based on the Representative Unit Cell (RUC) concept, in contrast to models based on the Representative Volume Element (RVE) concept. The RVE micro-model is a statistically representative sample of the heterogeneous material which has the same volume fractions of material phases and statistical distribution of inclusions, while homogeneous boundary conditions are applied to the boundaries of the RVE. The RUC concept assumes a simplified and perfectly arranged periodic microstructure with periodic boundary conditions on RUC boundaries. The RVE and RUC terms are often used interchangeably in the literature as discussed in e.g. [4,17,23]. Fig. 1 illustrates the RUC concept and basic discretization scheme of the micromechanical model employed in this work.

The discretization scheme of the micromechanical is shown in Fig. 2. A common feature of all micromechanical models based on the MOC is the discretization of the RUC using $N_\beta \times N_\gamma$ rectangular subcells. The subcells, as the structural elements of the RUC, are occupied by material phases. The most simple unit cells consist of only two phases (fibre and matrix for example), but the total number of employed material phases in the RUC is limited only by the number of subcells. The micromechanical model on the right-hand side image in Fig. 1 is one in which a composite material with 60% fibre volume fraction has been discretized using 20×20 subcells.

The theoretical background of the employed micromechanical theory is very complex and only the basic outlines of the localisation theory, which contribute to clarity of this article, are given in this work. The reformulated HFGMC theory approximates the displacement field within the subcell using the same second order Legendre polynomial as in the original HFGMC, after [15].

$$u_i^{(\beta,\gamma)} = \bar{\varepsilon}_{ij}x_j + W_{i(00)}^{(\beta,\gamma)} + \bar{y}_2^{(\beta)} W_{i(10)}^{(\beta,\gamma)} + y_3^{(\gamma)} W_{i(01)}^{(\beta,\gamma)} + \frac{1}{2}\left(3\bar{y}_2^{(\beta)2} - \frac{h_\beta^2}{4}\right) W_{i(20)}^{(\beta,\gamma)} + \frac{1}{2}\left(3\bar{y}_3^{(\gamma)2} - \frac{l_\gamma^2}{4}\right) W_{i(02)}^{(\beta,\gamma)} \quad (1)$$

Terms used in Eq. (1) are visualised in Fig. 2. In order to calculate the displacement and strain field within each subcell, the W microvariables have to be determined. The l_β and h_γ terms are subcell dimensions while $\bar{y}_2$ and $\bar{y}_3$ are subcell local coordinates, as illustrated in Fig. 2. The first term on the right-hand side of Eq. (1) represents the contribution of the homogenised (averaged) strain which is equal for all subcells in the unit cell. The rest represents

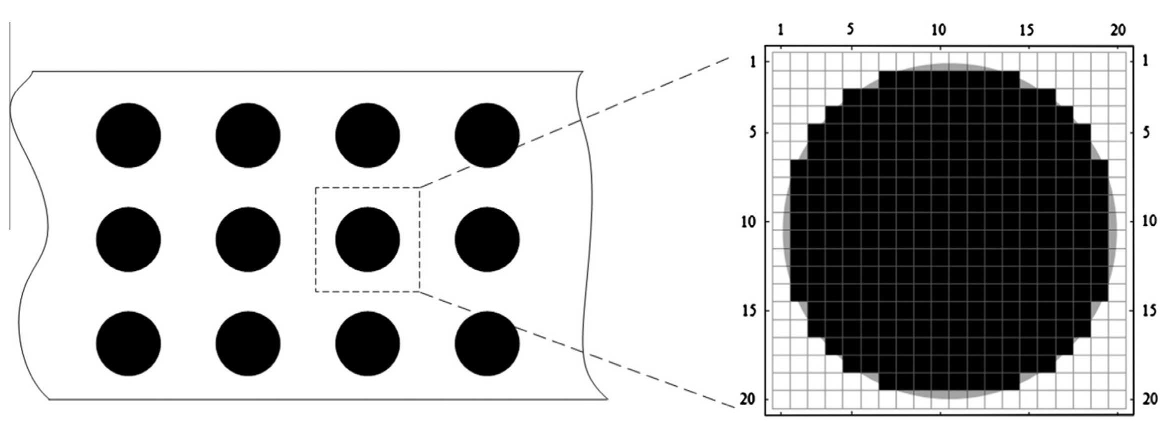

Fig. 1. RUC micromechanical concept and HFGMC unit cell discretization.