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Explicit multiscale modelling of impact damage on laminated composites – Part II: Multiscale analyses

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ABSTRACT

This work describes a multiscale impact damage prediction methodology for laminated composite structures which is based on the HFGMC micromechanical model and the MMCDM damage formulation. The numerical approach is intended for application within explicit finite element analyses and has been employed for modelling of high-velocity impact damage in laminated composite structures. Structural-scale applications and the multiscale framework of the method are presented in this paper whereas introduction and validation of the methodology have been presented in Part I of the paper.

By applying the described method, the micromechanical model calculates the local stress/strain fields within the unidirectional composite material, whereas the structural-scale computations have been performed employing Abaqus/Explicit. The Mixed Mode Continuum Damage Mechanics (MMCDM) theory has been utilised as to model the damage and failure modes of the composite material at the micromechanical level. As demonstrated in the Part I paper, the HFGMC and MMCDM model enable modelling of the microdamage nonlinearities at in-plane shear and transverse compressive loading of the composite plies. The micromechanical damage modelling approach has been employed at high-velocity soft-body impact on CFRP and GFRP composite plates in this work. Results of the multiscale damage model have been validated using available experimental data and by comparison with the numerical results obtained using the commonly used ply-level failure criteria and damage models.

1. Introduction

The primary load-carrying structural components of state-of-the-art aircraft structures are manufactured from composite materials. Examples of the advanced application of composite materials in the aeronautical structures are the wing box structure of the Airbus A380, the main spar of the A400M and the complete fuselages and wings of the Boeing 787 and Airbus A350 [1]. One of the key factors that contributed to the advanced applications of composite materials is the enhanced reliability of numerical procedures employed in the design of composite structures.

As to additionally enhance the reliability and accuracy of numerical failure prediction procedures used in the composite structural simulations, multiscale methods are being increasingly applied. A more detailed simulation of the physical phenomena has been enabled in these approaches since the micro-structural damaging processes are modelled explicitly in the micromechanical models.

The methodology described in this work is based on the computationally efficient reformulation of the High Fidelity Generalized Method of Cells (HFGMC) [2–4]. Since the methodology has been developed with the aim of being used in the explicit FE simulations, computational effectiveness has been considered a key priority. HFGMC belongs to a group of semi-analytical micromechanical models developed from the Method of Cells (MOC) [5]. These models present an excellent compromise between the accuracy of prediction of the local stress and strain fields within the composite RUC and the computational effectiveness. Consequently, they are attractive alternatives to FEM-based micromechanical models in applications within the multiscale framework. Currently, the GMC (Generalized Method of Cells) [6] is especially interesting for application in the multiscale framework due to the desirable computational properties [7–9].

The research presented in this work is a continuation of the previous research published in e.g. [10], where results of the initial stage of the multiscale methodology development have been shown. In the preceding paper, several micromechanical failure initiation theories have been investigated for application in the HFGMC/Abaqus multiscale framework. Further development of standalone HFGMC application, as well as the validation of the

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employed damage models, has been shown in the Part I contribution. Evaluation of the microdamage initiation models in [10] revealed significant discrepancies between the failure theories. These differences are evident in the values of the applied loading that initiates damage in the composite, as well as in the physical interpretation of the damage processes at the microstructural level. Consequently, the interference of composite failure modes has been diversely predicted by the failure theories.

The distinctive advantage of micromechanical damage models compared to the homogenised damage modelling approaches is that the microstructural damage mechanisms are explicitly taken into account in these approaches. Application of the multiscale techniques allows utilisation of micromechanical theories in the structural scale analyses, enabling the use of more detailed numerical formulation in the engineering applications, as shown schematically in Fig. 1.

The micromechanical approach in damage modelling applies failure criteria at the level of discretization of the micromechanical model, which is a single subcell in the HFGMC model. Initially, micromechanical damage theories in the MOC-based micromechanical approaches have modelled the damage processes by the instantaneous degradation of the subcell mechanical properties to a very low value, once a failure criterion has been satisfied [11–13]. Results of these applications suggest that Continuum Damage Mechanics principles also need to be included at the micromechanical level. Advanced applications of multiscale approaches are provided in e.g. [7,9], where the GMC model has been employed in impact damage analyses. The CDM principles have been used within HFGMC models only in recent articles and include models that capture the multiaxial nature of damage in composite materials [14]. In the focus of the most recent research is the problem of spatial dependence of damage processes in the multiscale framework [15,16].

The described multiscale approach has been employed in the numerical simulation of birdstrike damage prediction at composite aeronautical structures. Numerical procedures aimed at the birdstrike investigation are being increasingly improved as to complement experimental gas-gun testing, resulting in the reduction of the certification phase costs. Examples of the application of advanced numerical methods in the certification of existing aeronautical structures are provided in e.g. [17,18].

Birdstrikes belong to the group of soft-body impacts where the extreme stresses, generated in the impacting material, greatly exceed the strength of the impactor material, leading to its fluid-like behaviour. Consequently, several numerical obstacles have to be appropriately accounted for in the soft-body impact simulation as to obtain a reliable prediction of the induced damage in the impacted structure. Modelling of the extreme deformations of the bird material during impact and the load transfer on the impacted structure are two major difficulties in the numerical soft-body impact modelling approaches.

The multiscale methodology has been employed in the high-velocity soft-body impact simulations at CFRP and GFRP composite plates. As in the Part I contribution, the evaluated composite materials are the Silenka E-glass 1200tex/MY750/HY917/DY063 Epoxy and the T300/BSL914C epoxy composites (referred to as Silenka GFRP and T300/914 throughout this work). Parameters of the numerical soft-body impact analyses have been defined as to simulate the available experimental results. The structural response caused by a soft-body impact is specific as the impacting forces have been spread over a wide area. Therefore, gas gun experimental set-up and the results provided in [19] have been employed as references for the numerical multiscale damage prediction methodology in this work.

In addition to the previously described numerical obstacles, the multiscale approach introduces additional complexities into the soft-body impact numerical framework since the micromechanical model needs to be coupled to the finite element analysis. The approach which has been employed in this work is described in Section 2.

2. Multiscale methodology

Structural-scale numerical analyses have been performed in this work using the commercial FE code Abaqus/Explicit. The link between the structural-scale FE analysis and the HFGMC micromechanical computations has been established using the VUMAT subroutine that introduces user-defined constitutive models in the Abaqus/Explicit analysis.

The constitutive model of the material at the macro-scale has been determined by the HFGMC model in the multiscale methodology. Therefore, the homogenised Cauchy stress state at the end of the increment, as predicted by the user-defined constitutive law governed by the HFGMC model, has to be defined in the VUMAT subroutine. This task has been achieved by the application of the damage laws at the subcell level, whereas the effect of microdamage mechanisms on the homogenised mechanical properties has been subsequently included by application of the homogenisation as explained in Part I of the paper. More details and the theoretical background of the employed localisation and homogenisation procedures have been provided in the Part I paper.

The HFGMC model has been programmed in FORTRAN as a subroutine that is called for each material point in the VUMAT, as shown in the simplified flowchart in Fig. 2. The complete architecture of VUMAT subroutines is structured in a two-state arrangement, where the states refer to the Cauchy stress and parameters of the constitutive model at the beginning and the end of the current time increment.

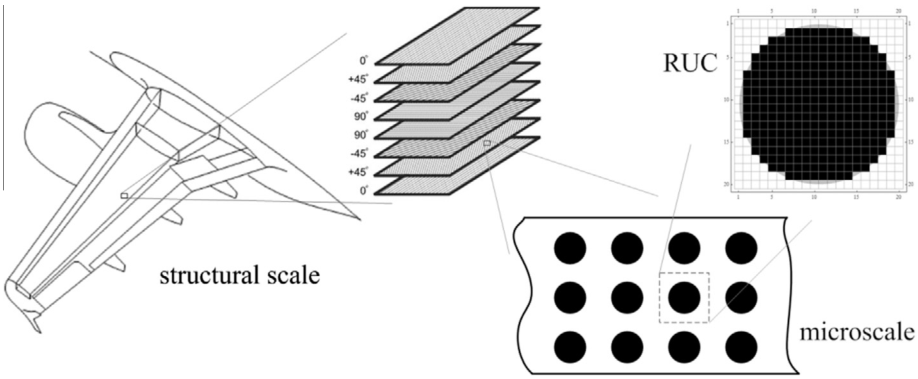

Fig. 1. Schematic representation of the length scales in micromechanical structural analyses.