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Multi-scale evaluation of the linear elastic and failure parameters of the unidirectional laminated textiles with application to transverse impact simulation

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ABSTRACT

Unidirectional laminated textiles (UDLTs) are flexible non-crimped fabric structures, the UD layers of which are bonded together by small amounts of thermoplastic resin and covered by polyethylene films over their external surfaces. Applications of them in ballistic protection clothes ensure lesser costs and ability to resist the penetration of humidity, which may substantially decrease the overall ballistic strength of the structure. This research focuses on the hierarchical multi-scale approach formulated for large displacement, material non-linearity and failure. The micro-scale model of UDLT represents matrix and fibres by means of 3D solid elements. A representative small volume (micro-cube) of the UDLT composite is subjected to a series of large deformation tests up to the failure, which enable to approximately evaluate linear elastic and failure parameters of the orthotropic shell elements that represent the mechanical behaviour of UDLT at rougher scale. Obtained longitudinal, transversal and shear strength parameters in association with the corresponding strains are the parameters used at mezzo-scale in order to calculate the Hashin criteria for the shell element failure. The results of the research are employed in order to achieve reasonable computational costs during the simulation of ballistic penetration through multi-layer UD composite textile structures at medium velocity range.

1. Introduction

Composite textiles consist of several materials with significantly different properties. Usually the material with low stiffness and therefore marked shear flexibility is reinforced with particles or fibres of much higher stiffness. Moreover, the properties of composites also depend on the length and distribution of reinforcing fibres. We focus on the unidirectional fibre composites in this research. Unidirectional composite textile consists of long fibres aligned in one direction, which are bonded together by the matrix material. The advantages of unidirectional composite fabrics are light weight (low density), high strength in the longitudinal direction, high impact strength and high strength-to-weight ratio. UDLT are widely used to manufacture lightweight high stiffness and strength products such as helmets, bullet-proof vests, aircraft parts etc.

Due to the complex internal micro-structure of UDLT, the simulation models of transverse impact on it are developed by employing multi-scale approaches. The multi-scale approach enables to simulate the structure by means of rougher models and simultaneously to retain all main features of the mechanical behaviour of the material. Most often two or three-scale model representations are applied. By using two-scale (micro-macro) approaches the internally multi-layer and multi-directional volumes of a composite structure may be presented by continuous shell or volumetric finite elements, where the equivalent properties of the material are obtained by investigating the characteristic behaviour of the selected representative volume element (RVE) of the composite. Within the RVE, the internal geometrical structure of the composite is represented as detailed as appropriate, by taking into account real possibilities of the simulation software employed for the analysis. Three-scale approaches introduce an intermediate scale (mezzo-scale), which still represents the most important formations of the modelled object by including them directly into the patterns of the finite element structure. However, the geometric patterns in the mezzo-scale are much more generalised and rougher compared against the micro-scale representations. As an example, the multi-filament yarns of the woven textiles presented by shell or solid elements is a typical example of the mezzo-scale, as they enable to represent explicitly the patterns of the weave including the contact interactions among the

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yarns [1–3]. The micro-scale model is employed for determining the material properties of the elements, which represent the yarn, while the corresponding macro-scale model presents the woven structure as continuous membrane, the properties of which are obtained by investigating the mechanical behaviour of the mezzo-level structure. In case of UDLT, the mezzo-scale represents a single UD layer by shell elements, while in the micro-level we tend to fully investigate the geometric pattern of the filaments and matrix material in contained in the RVE of the UD layer. In the mezzo-level multi-layer, multi-directional and multi-sheet textile structures are composed of UD layer shell elements by taking into account possible contact interactions, sliding and friction between adjacent layers. At the macro-level the multi-layer textile composite may be represented as orthotropic membrane, the properties of which are established by analysing the characteristic portion of the corresponding mezzo-scale model.

In the range of small displacements and linear behaviour of the material the usual approach is to compute the relation between the means of the stresses and strains over the statistically representative sample of material referred as a representative volume element (RVE) and to apply the effective properties in the macro scale. Another approach for evaluation of effective linear elastic material constants discussed in [4] was based on the analytical micromechanical models (direct and modified rules of mixture) and finite element (FE) modelling. Longitudinal, transverse and shear strengths of the UDLT could be evaluated by considering fibre shapes and their distribution [5], analytically or numerically. A generalised three-scale model was proposed in [6] for prediction of the strength of weaved, braided, stitched or knitted textiles, where material heterogeneities were modelled as a unit cell of UDLT with periodic boundary conditions in micro-scale. The homogenised parameters and stress–strain curves were obtained by using FE analysis. Similarly, the periodic boundary conditions were applied to RVE of hexagonal array in order to obtain the stress–strain curves by means of explicit FE analysis in [7]. The appropriate boundary conditions applied on the RVE of UDLT in each loading case were discussed in [8]. In case the fibres of the UDLT are aligned perfectly and the structure is periodic, the RVE is a unit cell of either hexagonal, diamond or square array [8,9]. Random defects can be considered by means of the RVE, which includes all microstructural heterogeneities that occur in the composite [10].

The aim of this research is to numerically evaluate the effective linear elastic and failure parameters of the unidirectional laminated textile (UDLT) by investigating large strains and stresses of the RVE. The main issue is to clarify if the failure conditions obtained from RVE analysis in the micro-scale can be directly applied for establishing the failure criteria of the equivalent model in rougher scale. The transition from micro to UD layer shell element at mezzo-level is performed by investigating the characteristic behaviour of the RVE of the composite material.

Low density polyethylene matrix reinforced with aramid fibres was used as a sample material combination in the micro-scale. Aramid is an important reinforcement material due to its high tensile strength and high stiffness, low density, resistance to high temperature and other useful properties [11]. Two kinds of FE models were used in this investigation. The micro-scale model assembled of solid elements represents the internal micro-structure of the UDLT and is computationally expensive. The RVE of this model was used to evaluate the relation between stresses and strains of the UDLT under the pure strain constraints. However, if pure shear is modelled with the assumption that the deformed RVE remains parallelogram with straight edges, the obtained shear moduli may depend on the size of the analysed RVE. This assumption is an overly restrictive constraint and the deformed RVE needs to satisfy only periodicity and symmetry conditions for the pure shear modelling [8]. These conditions were taken into account for modelling pure shear strains. The implicit FE analysis is employed to obtain linear elastic parameters such as Young's moduli in longitudinal and transverse directions, Poisson's ratio and shear moduli. The explicit FE analysis with slowly increasing displacements is employed to obtain failure parameters such as longitudinal and transverse tensile strengths, shear strength and respective strains. The Hashin failure criterion is employed in shell elements of the UD layer. This research may be considered as a further development of our recent work [12], where the UDLT plies subjected to ballistic impact were presented by three-zone FE models constructed at different scales. The known longitudinal failure strains of aramid fibres were directly used for the representation of the damage, however, a very important role was devoted for proper erosion strain values used in the model. It was demonstrated that proper combinations of failure and element erosion strains could be established for the models of certain refinement range and worked quite well, however, this lacked a solid theoretical background. The development in this work tends to establish these values at the level of RVE, as well as, convergence issues are considered. The numerical experiments of the sphere impacting solid and shell models are compared to adjust the erosion value of shell model.

Although misaligned fibres and other defects can occur during the manufacturing process, the material model with perfectly aligned fibres is analysed in this research. Moreover, it is assumed that the contact between the matrix and fibre system is perfect. The interface between matrix and fibre should be added otherwise [13].

2. Multiscale model

The multiscale model "bottom-to-top" was applied in this research. The internal structure of the UD layer of the composite layer and the properties of its materials are known in the micro-scale. The structure analysed in the micro-scale is assumed to be ideally periodic with square filling of the fibres. All fibres have square arrangements without any overlapping. The unit cell of the micro-level model consists of a cylindrical aramid fibre inserted into the cubic volume of the low density polyethylene matrix (Fig. 1). This type of the unit cell corresponds to square fibre distribution in the UDLT and can be applied for the composites if the filling does not exceed 78.5%. The hexagonal type of the structure should be used otherwise [7].

The stress–strain relation of the aramid fibre is almost linear until the failure (Fig. 2(a)). The matrix material, on the contrary, is elastic for small deformation only and undergo large plastic deformations (Fig. 2(b)).

The *MAT_PLASTIC_KINEMATIC material model (MAT_003) is employed in LS-DYNA to model the fibre and matrix materials with parameters in Table 1. This material model enables to simulate the failure of elements by defining the erosion strain value.

Model analysed in the mezzo scale is a small fragment of a macro model and represents the most important formations of the modelled object such as number of unidirectional layers and material properties of each layer that depend on the direction of fibres. Moreover, the interaction between the adjacent layers is considered in this scale. The layer of the unidirectional fibre composite in the mezzo scale is simulated using material model *MAT_LAMINATED_COMPOSITE_FABRIC (MAT_58). This model may be used to simulate composite materials with unidirectional layers, complete laminates and woven fabrics [14]. The failure surface type FS = 0 appropriate for unidirectional composites is applied in calculations. Linear elastic parameters, strength points with respective strains and erosion strain for this material model are evaluated using RVE in the micro-scale.