MESO-SCALE DAMAGE MODELLING OF TEXTILE COMPOSITE USING THE EMBEDDED ELEMENT TECHNIQUE AND CONTACT ALGORITHM

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Abstract

The paper investigates feasibility of application of embedded element technique to damage modelling of textile composites on an example of a woven laminate. The geometrical model of yarns is imported to Abaqus form WiseTex software. The yarns and matrix meshes are superimposed using embedded element technique. Damage initiation and development under tensile loading and the resulting stress strain curve is simulated using continuous damage mechanics approach based on Puck damage criterion and Zinoviev-type damage variables. The results show acceptable agreement with the damage modelling based on continuous mesh and with experimental data.

1. Introduction

Meso-scale unit cell finite element modelling (meso-FEM) is an important research direction in numerical simulation of mechanical behavior of textile composites and prediction of their stiffness, strength and damage properties. In this research, the unit cell modelling and damage initiation and propagation in 2D plain weave composite are investigated. The unit cell is modeled using the embedded element (EE) technique [1] that is based on non-continuous meshing techniques or mesh superposition.
Mesh superposition was proposed by [1], [2] and applied by [3]-[8] to modelling of textile composites to model elastic deformation. Its realisation in Abaqus (embedded element method) was assessed in our previous work for elastic analysis: stiffness properties and stress fields vs. conventional meso-FEM of fibre reinforced composites [9]. Different models: single UD carbon fibre, randomly distributed UD fibres, single crimped yarn and 5-harness stain composite – were compared with full/conventional method of meso-FE modelling.

There was reasonable agreement between the EE and full method for stiffness properties and elastic stress fields.
In the present work, to investigate the application of the EE method in damage modelling of textile composites, 2D plain weave E-glass composite with detailed experimental study from literature [10], [11] was used as benchmark. The composite was modeled in WiseTex [12] based on geometrical description and imported to ABAQUS for stiffness and damage calculations. The calculated results were compared with the experimental results of [10], [11]. There was acceptable agreement between the modelling and experimental results. A detailed modelling procedure of 2D plain weave composite in elastic and damaged regions will be discussed in the following section.

2. Model description

2.1. Unit cell

The unit cell is initially modeled in WiseTex [12] based on the geometrical information of the textile reinforcement. The modeled yarn volumes are imported to ABAQUS using a Python code. The matrix box is modeled and meshed separately. Then the "embedded element (EE)" technique is used to define the spatial relation between the yarns and matrix.
In the EE method the reinforcement parts mesh ("embedded part") is placed inside the matrix part ("host") mesh and the "embedding equation" is created for defining relation between degrees of freedom of the two meshes. Host part is the main part, which is considered as an independent model from the point of view of translational degrees of freedom (DOF). ABAQUS creates geometric relationships between nodes of the embedded and the host elements. If an embedded element node lies within a host element, the translational DOF's at the node are eliminated and the node becomes an "embedded node". The translational degrees of freedom of the embedded node are constrained to the interpolated values of the corresponding degrees of freedom of the host element [1]. The EE method effectively solves the problems inherent to the full method in meso-FE modelling of fibre-reinforced composites like interpenetration of the reinforced parts. In the present work, interpenetrations are eliminated using a contact algorithm applied to the yarns before the matrix volume is constructed.

2.2. Contact algorithm

The interpenetration of the reinforcement volumes in crossovers is typically present in geometrical models of the reinforcements [13]-[17]. In the current research the idea of "contact algorithm" based on the contact module of ABAQUS is implemented to cope with the interpenetration problem in unit cell modelling of textile composite. To eliminate the interpenetration problem, "penalty" formulation with friction coefficient of 1e-5 in tangential direction and "hard contact" method with "penalty" constraint in normal direction was applied between the surfaces of the reinforcement parts (impregnated yarns).
The contact algorithms are routinely applied in dry fabric modelling [18]. In continuous mesh models of impregnated composites contact formulations are not needed, as the yarns are "held in place" by continuity of the mesh. This, however, asks for resolving the interpenetration problem before meshing. When the EE meshes are used, the definition of contacts is necessary, as the interaction of the elements in yarns via constraint equations, linking their

displacements to matrix can be too weak in case of closely placed yarns. Definition of contacts resolves this problem – and simultaneously solves the problem of initial yarn interpenetration.

2.3. Damage algorithm

Continuous damage mechanics (CDM) has been widely used in meso-scale damage modeling of textile composites that describes progressive stiffness degradation of a rate-independent material. Here, for damage modelling, the yarn is supposed as a unidirectional flat ply laminate. The Puck criterion [19] is employed to predict the damage initiation and orientation as part of Zinoviev's type damage development algorithm, proposed by Ivanov [20].
To model the damage propagation, the damage evolution approach of Ladeveze is implemented based on the energy release rate [21]. The current formulation of the damage model uses Zinoviev's formulations, reformulated in [20], and stiffness degradation law from [22]. The damage model is described in more detail in [20]. It is implemented in a UMAT subroutine which updates the material properties of the yarns according to the amount of damage accumulated during the FE analysis in ABAQUS. The strength properties of impregnated yarns and matrix used in damage modelling are shown in Table 1.

3. Results

The strength properties and inclination parameters for damage modelling are used from [23]. The unit cell based on the EE method, contact algorithm and UMAT code is loaded in warp and weft directions using the periodic boundary condition. Finally, the damaged locations in the unit cell and stress-strain curve from the FEM are compared with the experimental results.

3.1. Homogenised stiffness properties

Figure 1 shows the WiseTex model of 2D plain weave composite. The unit cell dimension is 12.5×10.26×2.45 (mm). The parameters of the reinforcement are given in Table 1 [10].

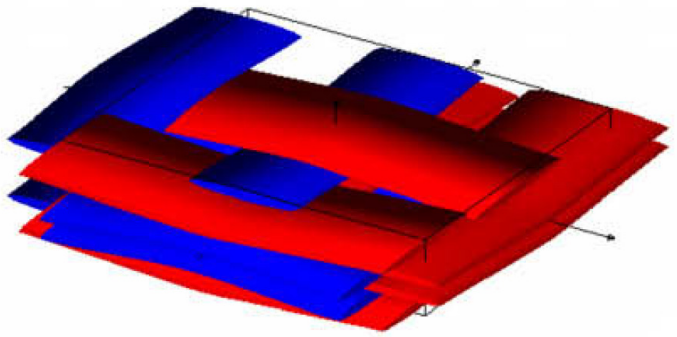

Figure 1 WiseTex model of 2D plain weave E-glass composite.

Strength properties (MPa)	Impregnated yarns
Longitudinal tensile strength	1725
Longitudinal compressive strength	620
Transverse tensile strength	40
Transverse compressive strength	130
Shear strength	70
Strength properties (MPa)	**Matrix**
Tensile strength	76
Compressive strength	118
Shear strength	88

Table 1 Strength properties of yarns and matrix used in damage modelling [23].

The WiseTex model is transferred to ABAQUS. The fabric in the plies is slightly unbalanced. A unit cell volume with flat faces is created by cutting off the "excess" parts of the yarns; the overall fibre volume fraction in the composite is preserved.
The mesh in the unit cell is created using the mesh superposition technique (Fig.2). The average aspect ratio of elements in yarns and matrix was 1.83 and 1.01, respectively. As could be seen in figure 2, the matrix and yarns are meshed independently and superimposed together using the "embedded element "method.

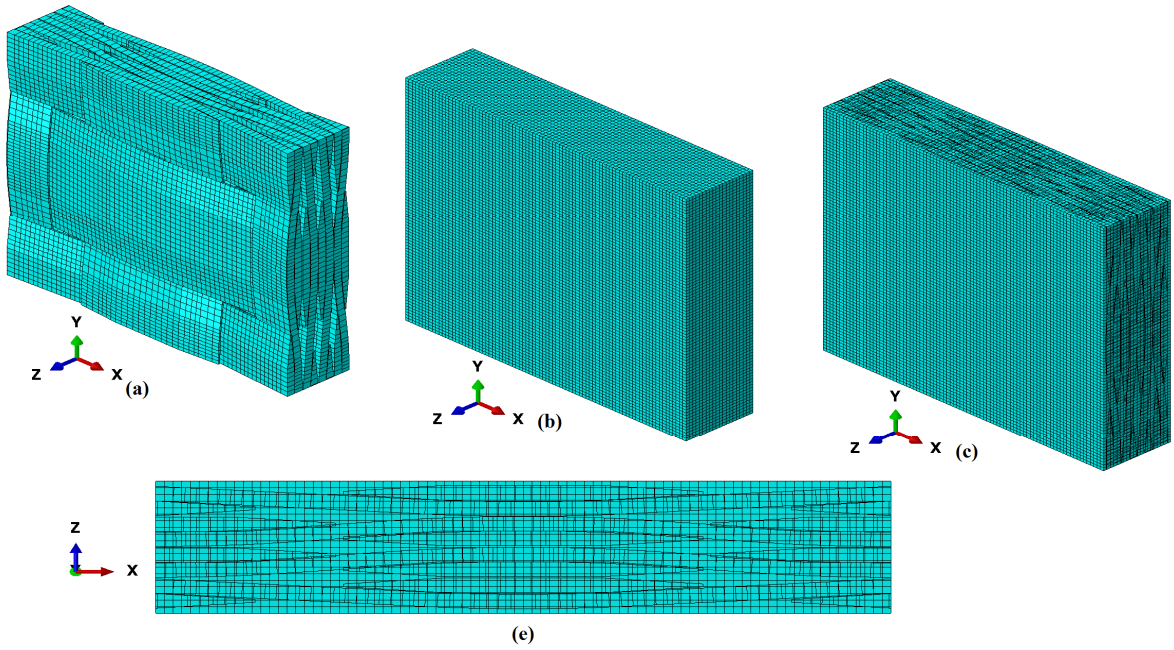

Figure 2 Unit cell model of plain weave composite in ABAQUS with the concept of embedded element method: (a) Yarns, (b) Matrix, (c) Superimposed yarns and matrix, (e) Side view of the unit cell.

The homogenized properties of the unit cell are compared with the results calculated by FE analysis with continuous mesh and experiment [10] in Table 2. The fibre volume fraction in both conventional and EE finite element models are somehow different from the experimental value because of transformation of certain change yarn volumes of the geometrical model when meshing. Table 2 shows values of fibre-direction moduli normalised for VF = 52%.

Homogenized properties	Finite element method, normalized for VF = 52%		Experiment [10], VF = 52%
	Embedded element (EE)	Full [23]	
E_X (GPa)	**24.1**	25.2	**26±1.5**
E_Y (GPa)	**23.8**	25.2	**26±1.5**
E_Z (GPa)	**7.96**	8.55	n/a
ν_{XY}	**0.140**	0.128	**0.207±0.091**
ν_{XZ}	**0.404**	0.402	n/a
ν_{YZ}	**0.405**	0.402	n/a
G_{XY} (GPa)	**4.02**	4.5	n/a
G_{XZ} (GPa)	**2.29**	n/a	n/a
G_{YZ} (GPa)	**2.28**	n/a	n/a
$E45°$(GPa)	**12.5**	n/a	**12.2±0.40**
$\nu 45°$	**0.486**	n/a	**0.610±0.148**

Table 2 Comparison of the homogenized properties for multi-layer plain weave composite from different methods: Finite element (EE method with contact algorithm, and full method), and experiment.

As it shown, there is a reasonable agreement between the EE and full methods for homogenized properties of 2D plain weave composite. The maximum difference between the EE and full methods is about 10% for in-plane shear modulus and Poisson's ratio (G_{XY} , ν_{XY}). The difference for Young's modulus in *X*, *Y* and *Z* directions is less than 7%. It should be noted that in the full finite element calculations the elastic moduli in fibre direction was normalised to the experimental for properties level of fibre volume [23].
The maximum difference between the EE and experiment for longitudinal and transverse stiffness properties is nearly 8%. Figure 3 compares the stress-strain curve for damage modelling of the 2D plain weave composite from author's method, Hoffman damage criterion using SACOM [23], and experiment [10]. In SACOM software [23] continuous meshes and Hoffman's stiffness degradation was used for damage modelling. Regarding to the symmetry of the unit cell, only single layer of the unit cell was used in the damage modelling.

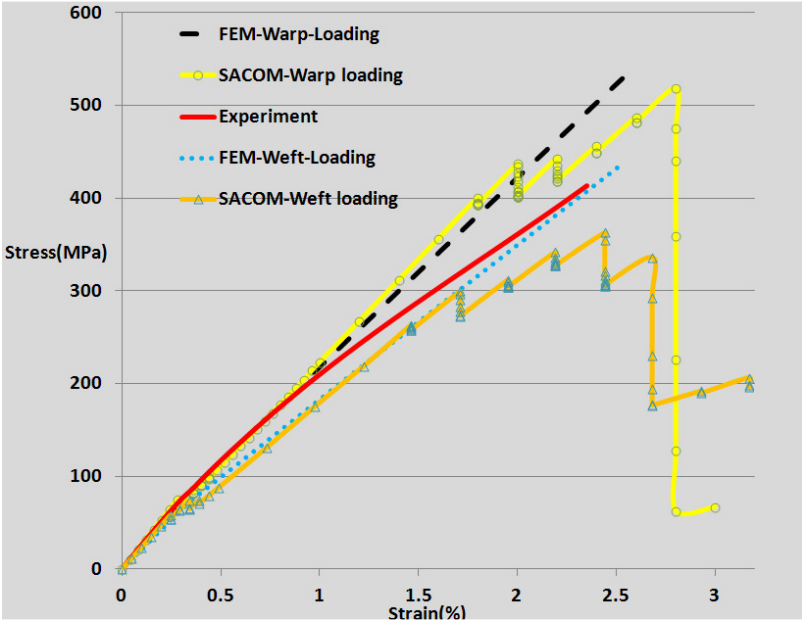

Figure 3 Comparison of the stress-strain curve for damage modelling of plain weave glass composites from EE (the present work), SACOM [23] and experiment [10].

As it shown, there is a reasonable agreement between the results. The predicted *E* modulus at the elastic region for authors' method has 7% deviation with experiment. Both SACOM and EE results over predict the failure and strength in warp loading. In weft loading of the unit cell the FE method has better results than SACOM with 5.9% and 7.8% difference with the experimental results for failure stress and strain. Figure 4 shows the stress patterns of S11 and S22 and damage initiation parameter in the weft yarns during warp loading of the unit cell.

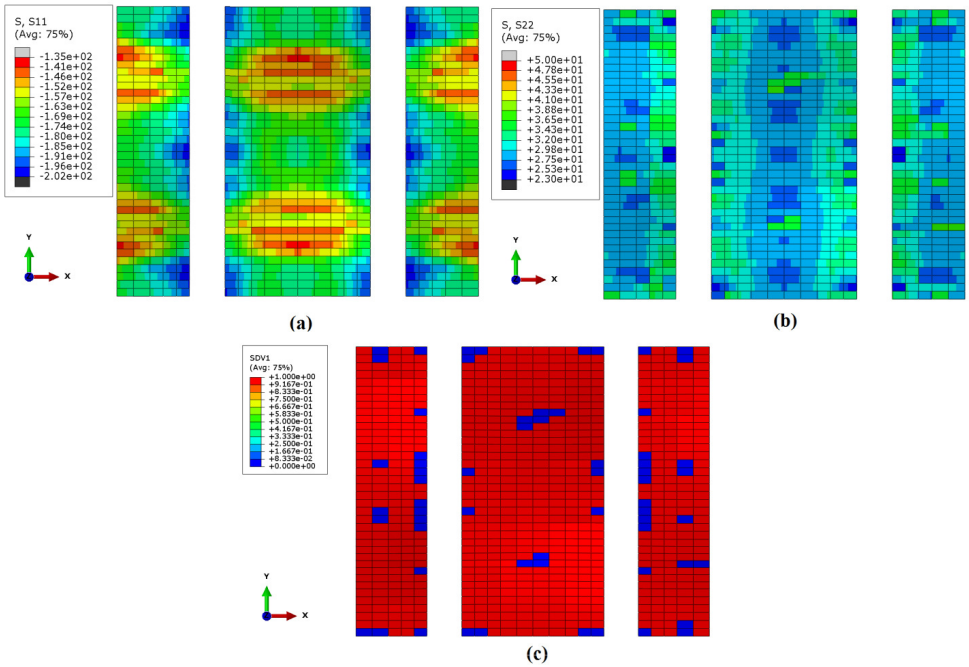

Figure 4 Stress patterns and damage evolution parameter in the weft yarns for warp loading of the unit cell: (a) S11, (b) S22, (c) SVD1 (Puck's criterion).

4. Conclusion

The feasibility of usage of EE method in meso-FE damage modelling of textile composites is confirmed after comparison with the continuous mesh solution and experimental data for a glass/epoxy woven laminate.
Contacts definition and a penalty contact algorithms were successfully applied in embedded elements FE simulation of a unit cell of textile composites for solution of yarn volumes interpenetration problem and for maintaining stability of the solution.

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