FINITE ELEMENT ANALYSIS OF 3D WOVEN COMPOSITE T-JOINTS UNDER TENSILE LOADING

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Abstract

Delamination was found to be a key factor in the initial non-linear load-displacement responses, for 3D woven composite T-joints under quasi-static tensile pull-out loading. This paper presents a voxel-based method to predict the non-linear response and damage initiation of 3D woven composite T-joints, by incorporating realistic fibre geometry and cohesive zone model (CZM) for meso-scale analysis. A feasibility study was carried out to justify the use of voxel mesh in CZM, as it has been an open research question in modelling composite failure behaviour. Difference from voxel and conformal cohesive models was identified. Recommendation for using voxel mesh in CZM was given. Simulation from the proposed FE models gives good agreement with experimental results for two different types of T-joints in damage onset mode and initial stiffness. This voxel-based method is efficient in modelling delamination and damage initiation of composite structures with complex fibre architecture, for which conformal mesh is not readily available.

1. Introduction

Composites with complex 3D fibre architecture are attracting growing interest from a number of industrial sectors, for their tailorable structural performance and advantages over laminated composites such as higher through-thickness properties. However, in most cases meso-scale modelling has to be adopted in FE analysis, as the anisotropic properties of these materials cannot be readily homogenised in a way like dealing with laminated composites. Thus to model a composite structure with complexity in fibre architecture, the first step is to build the reinforcement and matrix geometry and then meshing is performed based on the geometry[1]. For composites with complex fibre architecture or geometric features like curvature or holes, it is not always easy to obtain a 3D mesh where element connectivity is required as well as accurately representing the constituent domains, which is supposed to be, to some extent, out of the capability of current meshing software[2].

Voxel meshing method is an alternative to the aforementioned conformal meshing, and it has been proved to be an effective way in stress/strain analysis of composite structures but it might be lack of accuracy in failure analysis due to its step-like constituent interface though some good agreements with experiment results were found based on a number of proposed models for composite performance

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predictions[3, 4]. Comparison between voxel and conformal models of a multi-layer plain woven composite was studied by Doitrand and colleagues[5]. They found that voxel method shows good agreement with conformal method in terms of elastic properties but spurious prediction on damage initiation caused by stress concentrations is not negligible. However, mesh dependency was found by Ernst et al.[6] when using conformal mesh to analyse the failure of textile composites with fracture energy approach. Irregular elements defined as not having an aspect ratio of one would be usually generated at the constituent interface by mesh engine if the interface is not formed of flat surfaces, which were found as “crack stoppers” in the simulation when compared with results from a manually altered regular mesh with element aspect ratio close to one. Additionally, more irregular elements are normally to be expected in the interface for textile composites as they have more complex fibre architecture. Instead, voxel mesh was adopted by the authors as the mesh dependency problem vanished with this method, and also good agreement in elastic and progressive damage was observed between simulations and experimental results for the failure analysis of a thick NCF specimen subjected to three-point bending load.

Apparently, voxel method has both its cons and pros and sometimes a compromise of using voxel mesh has to be taken for modelling of composites with complicated fibre architecture when the conformal mesh is not readily available based on the state-of-art meshing technique while the voxel mesh is capable to achieve most of the required result. Delamination was found to be a typical failure mode in the mechanical tests of composite T-joints[7] and CZM was proven to be an efficient way to model the delamination in the FE analysis[8]. As a result, mesoscale models have to be employed to distinguish constituent interface for composites with complex reinforcement geometry as they could not be seen as a combination of homogenised lamina layers. However, it is open to doubt if it is feasible to use surface-based CZM with voxel method to model delamination as the interface elements will be generated on the step-like constituent boundaries in the mesh. Zhang el al. used voxel mesh to perform damage simulation of a single-layer triaxially braided composite with surface-based cohesive elements accounting for tow-tow delamination and good correlation with experimental results was obtained[4]. On the contrary, some authors claimed that it is not possible to do CZM with voxel mesh as generation of interface elements on step-like interface would be problematic[9], or the interface damage initiation and fracture energy cannot be computed on a step-like interface[10].

This study firstly evaluates the feasibility of the use of voxel mesh in surface-based CZM to model mixed-mode delamination for a T-piece composite structure which would raise the problem of massive step-like interface between matrix and yarns at the junction region due to voxel discretisation. Based on the conclusion, a voxel-based method to construct finite element models incorporating realistic fibre geometry and cohesive zone model(CZM) for meso-scale analysis is proposed to model the two types of 3D woven composite T-joints under tensile pull-off load. Good agreement is observed between simulation and experimental results for the composites’ non-linear load-displacement responses as well as different failure modes for the two types of T-joints.

2. Material

Vacuum-assisted RTM was used for moulding the composite T-joints comprising of IM7 carbon fibre preform and Gurit Prime 20LV epoxy resin. The preforms are based on 3D orthogonal weave with only variance in the junction, which are woven flat and folded into a T shape. The directions of yarns are marked in Figure 1. The preform consists of 8 layers of warp yarns and 9 layers of weft yarns in the web and 5 layers of warp yarn and 4 layers of weft yarns in the flange. Figure 1 from micro computed tomography(μCT) shows the weave pattern, Type 2, where half of the weft yarns are crossing over the other half at the T-junction, in comparison with Type 1.

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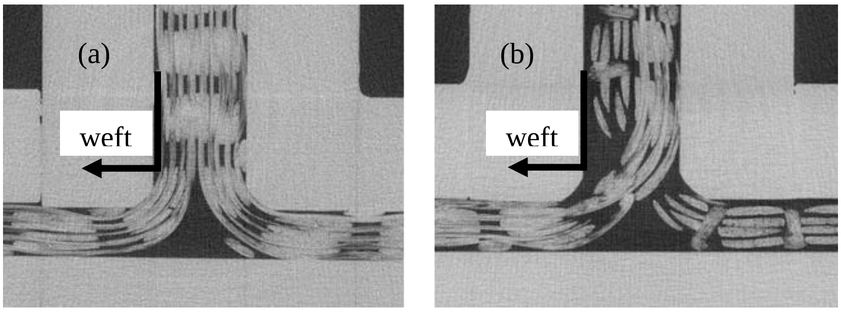

Figure 1. Images from µCT scan of the two types of 3D preform showing the weave variation in the junction region: (a) Type 1; (b) Type 2

3. Feasibility study for using voxel mesh in CZM

3.1 Geometry and meshing

Composite T-joints can be made from laminates, laminates with Z-pinning or textiles in the past decades for the sectors like aerospace or construction[8, 11, 12]. A simple laminated composite T-joint is constructed in TexGen(shown in Figure 2), with each half comprising of four layers of bent uniaxial non-crimp fabrics without any fixation material. The model aims to study the effect of inconsistent meshing on the mechanical performance of the structure with CZM. This geometry is also a reduced version for the studied 3D woven T-joints with orthogonal and binder yarns removed.

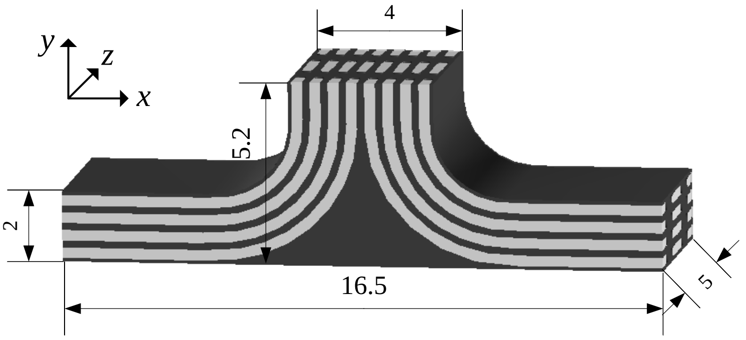

Figure 2. Geometry of the T-piece composite for feasibility study(unit: mm)

Voxel mesh of this T-piece composite is directly exported from TexGen along with the yarn element orientation database. Each of the voxel elements is either assigned to the matrix or a yarn set based on the position of voxel element centroid. Conformal mesh with hexahedral elements is generated by Hypermesh based on the geometry imported from TexGen. Hexahedral mesh generation accounts for most of the model development time due to the geometric complexity imposed by geometric features of the T-piece. Both of the meshed meso-scale models are presented in Figure 3. By comparison between the two types of mesh, it is found that the inaccuracies of voxel discretisation lie in the following two aspects: 1) the voxel discretisation generates step-like surfaces for the constituents, and it becomes more compelling when it comes to the geometry with curvature; 2) voxel discretisation loses the geometric feature of yarn cross-section shape when it is not rectangular. For the FE analysis, element type of 8-node linear brick with reduced integration is assigned to the voxel and conformal mesh. Both of the meshed models are subjected to a tensile pull-off load as the mechanical tests performed on the 3D woven T-joints and mixed-mode delamination is expected. A convergence study without cohesive interface was also carried out to determine the element size in the models.

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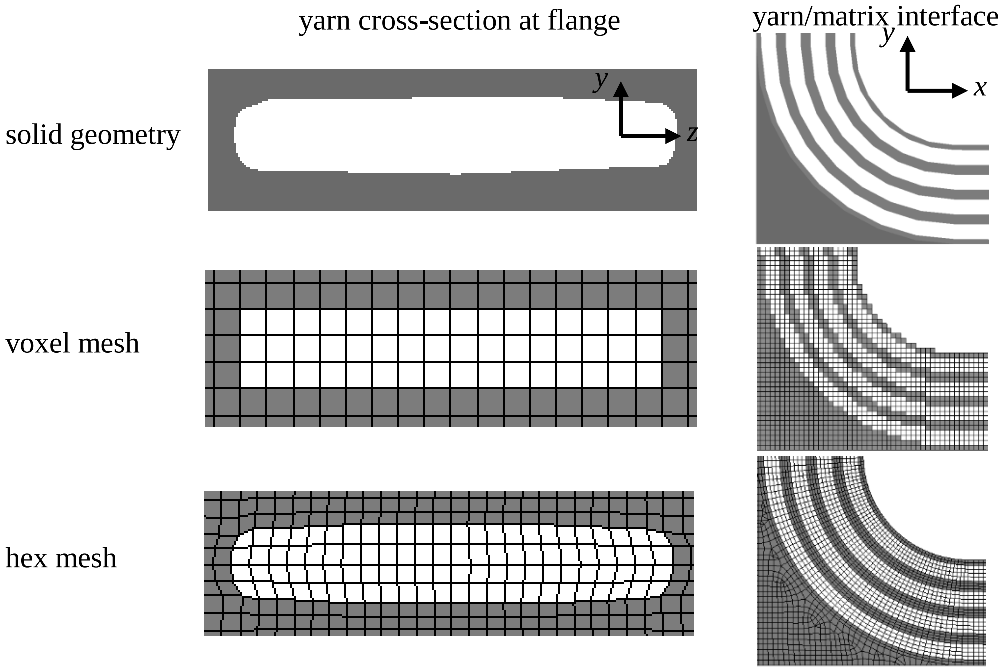

Figure 3. Mesh discretisation of the solid geometry of a half composite T-joint

3.2 Interface formulation for CZM

The thickness of constituent interface in composite materials is usually negligibly small. Surface-based cohesive modelling method is more suitable for modelling composite delamination than cohesive element method taking into account of the interface thickness effect. The surface-based cohesive behaviour has been implemented in Abaqus with damage initiation and evolution models. It has been widely tools to model composite delamination. The surface-based cohesive behaviour correlates cohesive tractions in the normal, first shear and second shear directions(t_n, t_s and t_t) with their corresponding separations(δ_n, δ_s and δ_t) in the same direction through a bilinear constitutive law. The areas under the tractions and their corresponding separations excluding the recoverable energy denote the energy release rate, G_n, G_s, and G_t, for each delamination mode[13]. The slope k is referred to as interface stiffness with subscript denoting its direction. An equation to estimate the minimum value of interface stiffness was proposed by Turon et al.[14] in order to ensure that the composite structure's elastic properties are not decreased by the presence of cohesive surface before crack propagation due to the bilinear relation between tractions and separations, though it is only based on mode I delamination. Minimising the fictitious global compliance resulting from cohesive behaviour prior to crack development is regarded as a necessary condition for a successful FE analysis with CZM. In addition, parametric study has shown that there is a converged state for the global compliance in terms of interface stiffness so that using extremely large value of k is not recommended as it will significantly increase computation cost and cause numerical instability. As the T-piece composite is supposed to have mixed-mode delamination under the tensile pull-off load, quadratic stress criterion for the damage onset is adopted and thus when the following expression reaches a value of one, damage is assumed to initiate:

$$\left\{\frac{\langle t_n\rangle}{t_n^0}\right\}^2+\left\{\frac{\langle t_s\rangle}{t_s^0}\right\}^2+\left\{\frac{\langle t_t\rangle}{t_t^0}\right\}^2=1 \qquad (1)$$

Where t_n^0, t_s^0 and t_t^0 denote the initial failure stress in the normal, first shear and second shear directions under each of the single-mode delamination, respectively. The symbol <> is MacAuley operator. After damage initiation, there is a linear softening on interface stiffness until total fracture of the interface based on the mixed mode power law for damage evolution:

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$$\left\{\frac{G_n}{G_n^C}\right\}^{\alpha}+\left\{\frac{G_s}{G_s^C}\right\}^{\alpha}+\left\{\frac{G_t}{G_t^C}\right\}^{\alpha}=1 \qquad (2)$$

Where G_n^C, G_s^C and G_t^C are the critical energy release rate values in the normal, first shear and second shear directions under each of the single-mode delamination.

3.3 Results and discussions

In the feasibility study, the meso-scale models are simplified only to have interface damage with elastic properties used for the constituent materials. The interface properties used in the cohesive models are listed in Table 1 and they are comparable with those used by the previous studies for carbon fibre/epoxy interface[15, 16].

Table 1 Interface properties used in the cohesive models

$k_n = k_s = k_t$	$t_n^0 = t_s^0 = t_t^0$	G_n^C	G_s^C	G_t^C
10^6 MPa/mm	60 MPa	0.2 mJ/mm^2	0.84 mJ/mm^2	0.84 mJ/mm^2

Figure 4Figure 4 shows the load-displacement responses for the meso-scale cohesive zone models in comparison with the result from perfect bonding model. Both of the voxel and conformal models with cohesive surface predict extensive interfacial failure when the applied force on the T-piece composite reaches approximately 750N. The composite gradually lose its structural integrity above 750N due to delamination. Also the study verified that cohesive behaviours in the models would contribute to the structure compliance, The conformal model exhibits more significant degradation in stiffness than the voxel model during the loading step, although the same interface properties(Table 1) were used. Moreover, the interface of the conformal model tends to initiate the damage earlier than the voxel model, but the damage on the interface of the voxel model propagates much faster after initiation. In order to rule out the influence from interface damage on the structure compliance, the initial failure stresses and the critical fracture energies were scaled up to 10 times of the original values. The load-displacement responses for the two models are plotted as the dashed lines in Figure 4. There is still a difference in stiffness between the voxel and conformal models. Because the conformal model could represent the geometry and interface more accurately than voxel model, it is considered to have higher accuracy. In addition, the accuracy of cohesive element method depends on sufficient number of elements within the cohesive zone[16]. The finer voxel mesh(0.05mm) was further analysed based on the same conditions. No difference in stiffness was found with the previous voxel model(0.1mm). Based on the FE analysis of this T-piece composite with meso-scale cohesive models, it is concluded that the voxel mesh model could be used in CZM. It is capable of capturing the peak failure load in the mixed-mode delamination analysis. But it would show a higher stiffness which is likely to be an inherent problem due to its inaccurate discretisation of the geometry. This limitation in stiffness over-estimation may not be critical, particularly at the conceptual material design stage.

Parametric study was performed by varying the interface strength and the interface stiffness. However, the load-displacement responses for the models with lower interface strength show the similar stiffness with those in Figure 4. The damage initiation occurs earlier depending on the value of interface strength. The effect of interface stiffness was also investigated. For both of the voxel and conformal models, the global compliance would converge when the interface stiffness is larger than 10^5MPa/mm, which is at similar order of magnitude with [14]. Use interface stiffness lower than the converged value would introduce a spurious compliance on the structure. If the interface stiffness is reduced by one order of magnitude from the converged magnitude, the voxel model would show a similar load-displacement response with the conformal model. In the voxel-based cohesive models, interface

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stiffness scaling is found to be a possible way to improve the accuracy of using voxel mesh for delamination modelling.

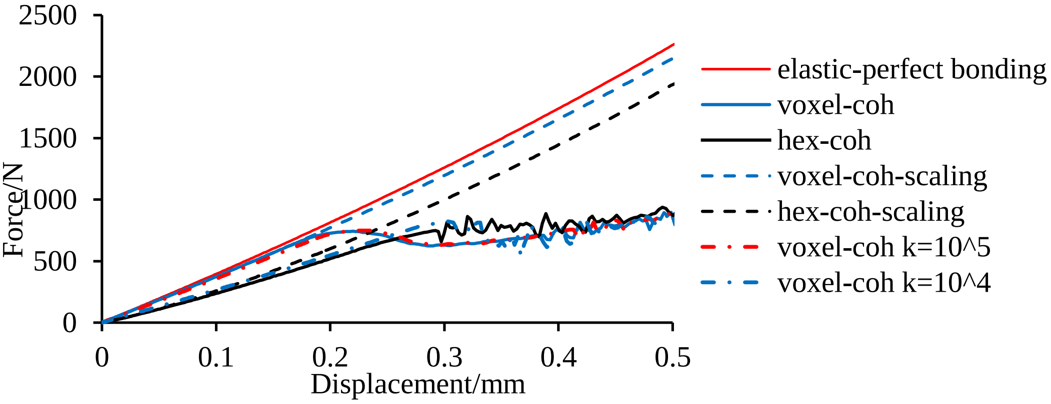

Figure 4. Load-displacement responses for models with cohesive behaviour

4. FE Models of 3D woven composite T-joints

4.1 Geometry and meshing

The reinforcement geometries of the two types of 3D woven T-joints are modelled using TexGen, based on the geometric parameters of yarns extracted from µCT analysis. Benefiting from the periodic fibre architecture of the reinforcements, only a repeat unit was modeled along its x-axis direction, as illustrated in Figure 5. The two geometries comprise of identical unit cell of orthogonal weaves, with the different weave patterns at the junction regions. The length of the web in the geometric models is reduced, as the FE analyses found that the deformation in the web was negligible in comparison with the bending of flange. Voxel meshes are generated in TexGen based on the above reinforcement geometries providing an element size of 0.1mm.

4.2 Constituent properties and material failure criteria

Without using an averaged intra-yarn VF for the whole models, variation in the intra-yarn VFs for warp, weft and binder yarns is considered, which is respectively calculated by matching the VF of the composite in each direction. The transversely isotropic properties of yarn are calculated based on the Chamis model[12]. Hashin's failure criteria for the yarn[17] is used here to capture damage initiation, while matrix damage is evaluated by the pressure dependent modified von Mises criterion[18]. FE models are solved by Abaqus Explicit with a user-defined material subroutine. Because both of the two types of T-joints are made of same materials in same fibre volume fraction, identical material and interface properties are therefore used in the FE models for simulation of the tensile pull-off tests.

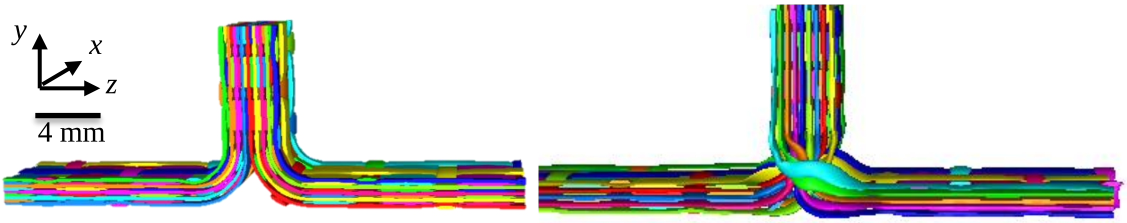

Figure 5. Geometric models for Type 1(left) and Type 2(right) 3D woven T-joints

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5. Results and discussions

In the mechanical tests, the two types of T-joints showed the same initial stiffness but different failure modes for damage initiation, which leads to a significant difference in peak failure loads[7]. Delamination was arrested in the Type 2 T-joint due to the weave variation in the junction. Figure 6 shows the FE results of force-displacement responses up to damage initiation, in comparison with test results. Good agreement is obtained in initial stiffness for the two types T-joints. The cohesive elements in the models were able to capture the non-linear responses. The FE models predicted the different failure modes of damage onset for the two T-joints, i.e. delamination in junction for Type 1 and resin damage for Type 2. The damage predicted by the FE models was later than that in the tests.

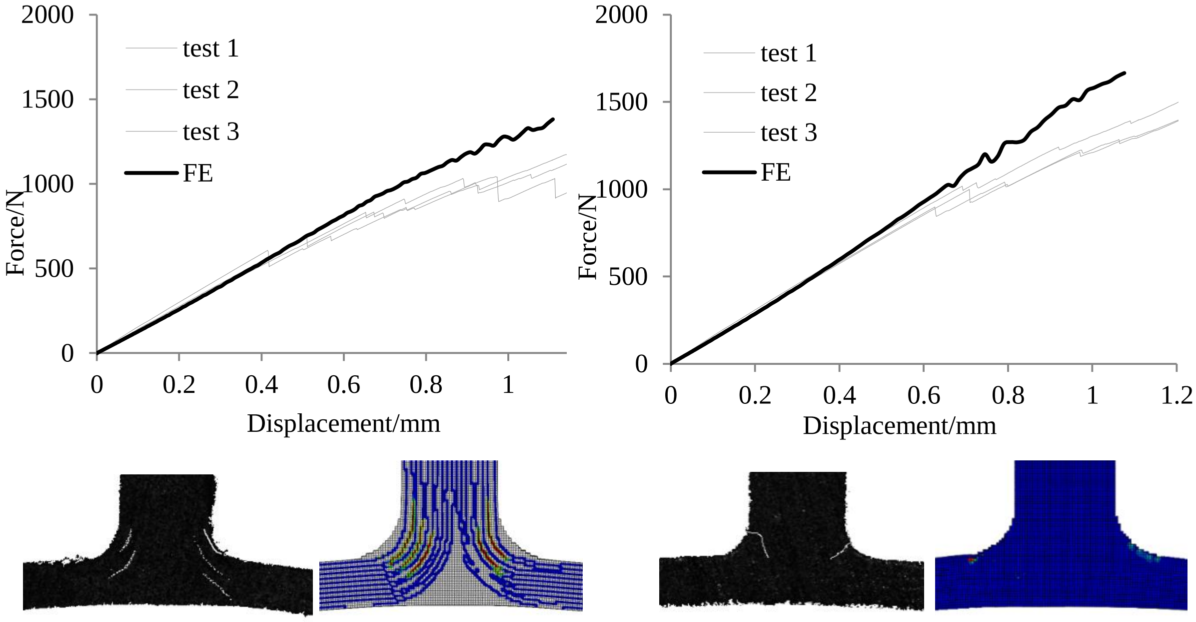

Figure 6. Predicted load-displacement responses and initial failure modes for Type 1(left) and Type2(right) T-joints in comparison with test results; FE contours: left shows interface damage parameter for T-joint Type1; right shows resin damage parameter for T-joint Type2.

6. Conclusions

A voxel-based method to construct finite element models incorporating realistic fibre geometry and CZM for meso-scale analysis of 3D woven composite T-joints was proposed. The method was based on the feasibility study of voxel mesh validity in CZM. The proposed FE models successfully captured the non-linearity in the initial stiffness, the difference in initial damage loads and the initial failure modes shown in the mechanical test. The study has showed that the voxel-based method is efficient in modelling delamination and damage for composites with complex reinforcement, with the advantage in meshing.

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