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# The effect of mesh morphologies on the mesoscale Finite Element modelling of woven composites

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**Abstract**

Mesoscale Finite Element (FE) modelling methods of woven and braided composites have attracted great attention in recent years as they can provide high accuracy, especially in describing damage behaviour. One of the key factors that affects the results of such kind of simulations is the choice of the mesh morphology. The two most widely-applied meshing approaches at present are the voxel- and the volume-mesh; however, these two models have not been compared in detail with experimental data. Therefore, in the present work, both volume- and voxel-mesh models have been used to build a composite Representative Volume Element (RVE) made of glass-fibre woven fibre with Epoxy Ampreg 26. These FE models have been built in order to investigate the effects of the mesh morphology on the simulations under quasi-static tensile and shear loading conditions. The volume-mesh model provides a well correlated stress-strain relationship in comparison with the test results, while the voxel-mesh model predicts higher tension and shear properties. However, computational issues, such as negative volume and the stress concentration caused by the mesh, are observed in the volume-mesh model while the voxel-mesh is computationally more efficient, *i.e.* less time-consuming, in replicating the tension and shear tests with acceptable results.


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*Keywords:* woven composite; unit cell; voxel mesh; volume mesh

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## 1. Introduction

Composite materials have been widely investigated because of their applications in many fields. One of the features of composites is that they are mostly manufactured with a complex fiber texture in order to improve the mechanical properties under different loading conditions. This construction poses several issues also for building reliable and efficient models, especially Finite Element ones. These models should be useful to assess and predict the strength, up to failure, of such materials under service loads. However, the replication of damage features using macro-homogeneous approach is not straightforward. Specific failure criteria, able to replicate different kinds of heterogeneous failure (including fibre breakage, fibre-matrix debonding, matrix cracking or delamination) in a homogeneous framework are required. A promising but challenging method to study the composites, particularly with regards to the failure mechanism, is to build a full structure of the unit cell exploiting a mesoscale approach. Mesoscale models are, in fact, supposed to accurately predict the mechanical behaviour of the assembled composites even with simple material models employed (Bresciani *et al.*, 2016, Manes *et al.* 2014) due to the fact that the failure conditions are defined directly on the constituents. However, several issues arise while exploiting this approach. The mesh generation of the mesoscale model in a finite element (FE) method is an actual challenge. At present, there are many different meshing methodologies: among these, the voxel- and volume-mesh are widely used.

The volume-mesh discretizes the geometry of the constituents of the composite exploiting tetrahedral elements. This choice allows the accurate description of the geometry, especially for some complicated structures *(Bouchard et al.*, 2018; Chen *et al.*, 2019; Wehrkamp-Richter *et al.*, 2018; Zheng *et al.*, 2019). Wehrkamp-Richter *et al* (Wehrkamp-Richter *et al.* 2018) used the volume mesh to investigate the mechanical properties of the braided composite because the mechanical property is very sensitive to the structure of the yarns, which can be built precisely by the volume-mesh model. Moreover, the volume-mesh has been efficiently applied on structures with small voids inside (Bouchard *et al.* 2018). Additionally, to investigate the mechanical properties, the volume-mesh can play an essential role in the study of other properties, such as moisture diffusion (Zheng *et al.*, 2019). Results provided by the volume-mesh were in good agreement with experimental data, and further predictions (of the mechanical parameters) based on volume mesh model were proved to be accurate (Bouchard *et al.*, 2018; Chen *et al.*, 2019; Chowdhury *et al.*, 2019b, 2019a; Wehrkamp-Richter *et al.*, 2018; Zheng et al., 2019). However, to build an effective numerical model, the volume-mesh model should be combined with precise scanning and reproducing software (Bouchard *et al.* 2018; Chen *et al.* 2019; Chowdhury *et al.* 2019a) coupled with time-consuming analysis on the mesh morphology and complex programs to generate the accurate mesh morphologies.

The voxel-mesh model has also been widely employed in the mesoscale modelling of complex structures *(Ma et al.*, 2019; Song *et al.*, 2018; Yan *et al.*, 2019; Zhang *et al.*, 2014; Zhao *et al.*, 2019), and the results can be validated by calibration experiments (Ma *et al.*, 2019; Zhang *et al.*, 2014), such as tensile and shear tests (Song *et al.*, 2018). Moreover, the predictions proposed based on such combined models can be successfully used on other large scale models (Ma *et al.*, 2019; Zhao *et al.*, 2019). The voxel-mesh model can be easily built ignoring the detailed geometry of the structures and, consequently on the contrary to the volume-mesh model, no scanning of the geometry details is required. However, the refinement of the geometry is required during the generation of the voxel-mesh and some features, such as the contact surface and the waviness of the fibre, might be lost in this process (Scazzosi *et al.*, 2018). Small differences compared with the experimental data can also be observed in some cases (Ma *et al.*, 2019).

According to the previously described existing studies, both the volume- and voxel-mesh have a wide application in mesoscale modelling. Good results fitting experimental data can be obtained and, furthermore, the accurate prediction of these two approaches can be exploited for further macroscale studies. However, some issues may hinder their application and only a few studies have compared these mesh morphologies. In addition, a detailed comparison with experimental data has, at present, not been performed. Based on the elastic behaviour, stress field and damage initiation, Doitrand *et al* (Doitrand *et al.,* 2015) investigated the difference between the simulated results obtained with these two meshing methods showing that the elastic properties can be accurately predicted by both meshes, with the volume-mesh being more suitable to replicate the damage localization. However, a simple loading condition was used in that work and the effect of the mesh was investigated individually since the mesh size and the number of elements were different for the two mesh morphologies, making the work unsuitable to identify the difference between the mesh morphologies. The simulated results from the voxel- and volume-mesh were also compared in a study of the mechanical properties of a trabecular bone (Ramos-Infante and Pérez, 2017). The results from both models showed a good agreement with the experimental data, but the volume-mesh model required a considerably higher computational time.

In the present article, both voxel- and volume-mesh models were built in order to replicate the tensile and shear behaviour of a woven composite reinforced with glass-fibre. The composite was made of R-glass fiber and Epoxy matrix Ampreg 26. The behaviour of the mesh morphologies is investigated based on the stress-strain curves, the damage onsets and the computational effort required. Moreover, the results from the numerical simulation are compared with the experimental data presented in a previous work (Ma *et al.*, 2019).

## 2. Numerical model

A FE model, describing the unit cell of the composite under investigation containing both the matrix and fibre, was built based on the images of the real structure of the woven composite, as shown in Fig. 1. The dimension of the present unit cell is $10 \times 10 \times 0.6$ mm$^3$, and the width of the yarn is 4.0 mm with the span of 1.0 mm. The same geometry parameters were used for building both models. Detailed information of the FE model is reported in Table 1. In the volume-mesh model, the weight fraction of the fibre exactly corresponds with the designed value, while for the voxel-mesh model, the weight fraction of fibre is lower but still acceptable compared with the sample. The total number of elements is kept similar, being around 50000 in order to compare the two morphologies. Both models are built in combination with the software TexGen®, a textile geometric modeler developed by the University of Nottingham (Long and Brown, 2011).

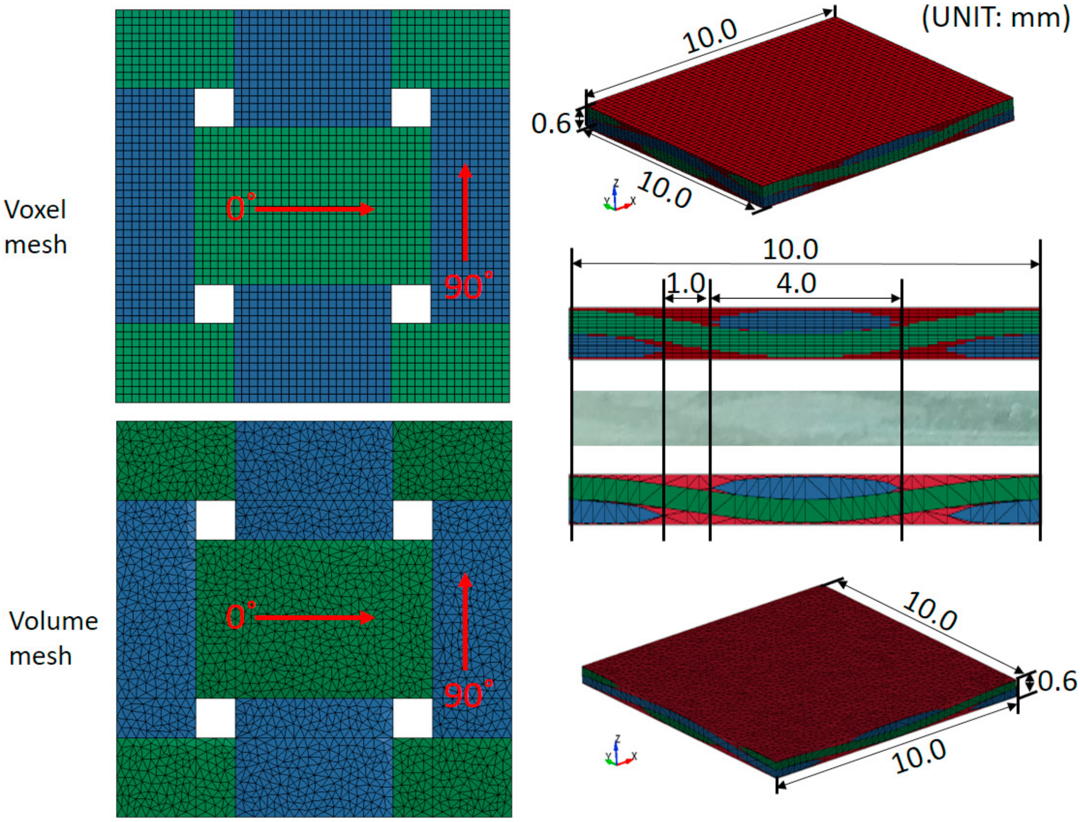


Fig. 1 The FE model using voxel- (upper) and volume- (lower) mesh compared with the real woven composite

Table 1 Details of the FE models and the sample

| | Weight fraction of the fibre | Number of elements | | |
|---|---|---|---|---|
| | | Fibre | Matrix | Total |
| Sample | 73 (±5) % | - | | |
| Voxel-mesh | 72.8% | 26944 | 23056 | 50000 |
| Volume-mesh | 73.0% | 18742 | 31800 | 50542 |

Regarding the material model employed in the present FE model, Table 2 lists the material parameters. The linear elastic model was used to describe the mechanical response of both the fibre and the matrix, while the ADD_EROSION (MAT_000) in LS-DYNA® was employed for the element deletion with the failure process determined by the equivalent strain (for the matrix) and the principal stress (for the fibre). The strain limit of the matrix and strength of the fibre are reported in Table 2. The voxel-mesh used the fully integrated quadratic 8 node solid element, whose ELFORM is 3 in LSDYNA. Whereas in the volume-mesh model, the 4(5) point 10-noded "composite" tetrahedron (ELFORM=17) was employed, which is also quadratic and similar to the element used in the voxel-mesh for achieving high accuracy.

Table 2 Material parameters used in the FE model

| Property | Fibre | Matrix |
|---|---|---|
| Material type | R-glass fibre (Rovings.) | Epoxy Ampreg 26 (E-composites) |
| Elastic modulus (GPa) | 90 | 3.92 |
| Shear modulus (GPa) | 12.90 | 1.70 |
| Tensile strength (MPa) | 4875 | - |
| Tensile failure strain (%) | - | 3.21 |
| Density (g/cm3) | 2.55 | 1.11 |

In the FE model, the bonding between the fibre and matrix was described by AUTOMATIC_SURFACE_TO_SURFACE_TIE-BREAK, which requires the normal (NFLS) and tangential (SFLS) strength. When the normal ($\sigma_n$) and shear ($\sigma_s$) stresses meet Eq. (1), the interface can fail, which indicates that debonding occurs. In the present model, the normal and the tangential strength are equal to 27.6 MPa and 10.3 MPa, respectively (Ma et al., 2019).

$$D = \left(\frac{\sigma_n}{NFLS}\right)^2 + \left(\frac{\sigma_s}{SFLS}\right)^2 \geq 1 \tag{1}$$

The boundary conditions of the unit cell should keep the displacement of every surface equal along its normal direction. Therefore, the CONSTRAINED_NODE_SET was used on every outside surface for this unit cell. The tensile and shear loadings were achieved by displacement.

## 3. Results

The simulated tensile results from the volume-mesh and voxel-mesh models compared with the experimental data (Ma et al., 2019) are shown in Fig. 2. Experimental data are presented in a grey area that reproduces the experimental spread. In both models, debonding between fibre and matrix occurred first. Subsequently, the matrix cracked causing a small drop observed on the slope of the stress-strain curve. Finally, the fibre broke, leading to the peak stress of the composite. A similar damage history process was also reported in the work of Doitrand *et al* (Doitrand *et al.*, 2015), validating the reliability of the prediction by the present models on the damage onsets. Moreover, the results from both the volume-mesh and voxel-mesh models closely resemble the experimental data (considering the spread of the experimental data), confirming the acceptable reliability of the present models. To quantify the prediction capability of the two modelling approaches, the detailed results from the simulation, are listed in Table 3, showing that the elastic modulus replicated by the volume-mesh model matches the experimental data well, especially considering the spread of the experimental results (as reported in Fig. 2 and Table 3) , while the strength predicted by the voxel-mesh model matches the experiments more accurately. However, both predictions are acceptable and all the debonding, the matrix cracking and the fibre breakage happen at a similar strain. The prediction of the damage onsets under the tensile loading seems therefore to be reliable. Specifically, the prediction by the voxel-mesh shows an accurate prediction of the strength properties, which is of interest for engineering applications.

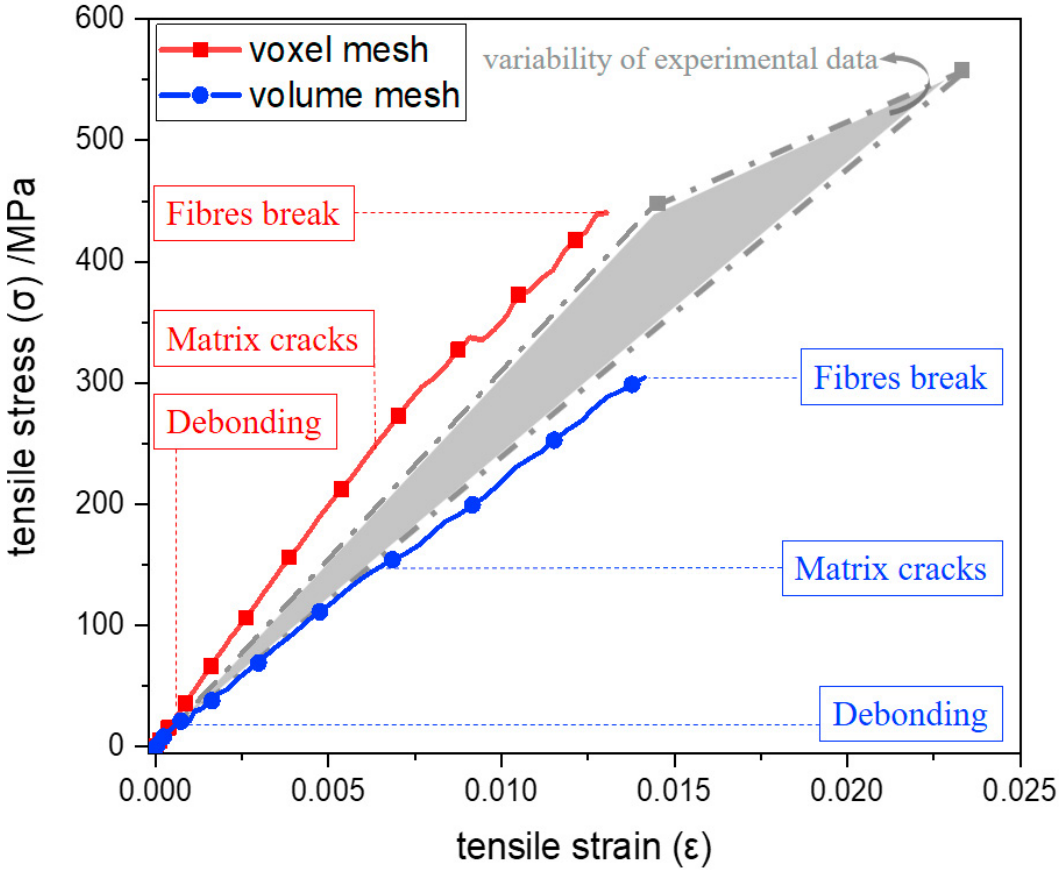


Fig. 2 Comparison of experimental data (Ma *et al.*, 2019), with volume-mesh and voxel-mesh simulations with respect to the tensile behaviour

Regarding the shear behaviour, the simulated results compared with the experimental data (Ma *et al.*, 2019) are presented in Fig. 3, showing that the modulus provided by both the volume-mesh and voxel-mesh models are identical and in good agreement with the experimental data, being 5% larger than the value obtained from experimental tests, according to Table 3. Additionally, it should be noted that the modulus is calculated at the beginning of the curve before the onset of damage in the matrix. For instance, the slope of the stress-strain curve from the volume-mesh model reduces as the matrix crack occurs (see Fig. 3), nevertheless, the modulus is obtained before the failure of the matrix. According to Fig. 3, the results from both the volume- and voxel-mesh models are identical at the beginning of the stress-strain curves, which therefore have the same modulus as reported in Table 3. Also, as under tensile loading conditions, both models similarly predict the damage onsets due to debonding and matrix cracking. Considering damage onset, there is almost no fibre damage in the shear test, the stress-strain curves end with the collapse of the structure instead of the erosion of the fibre, unlike the composite under tensile loading. As a result, loading is carried mainly by the matrix and the matrix-fibre interface, which was previously proven by Zhao *et al* (Zhao *et al.*, 2019). The debonding occurred in the early state of the loading process, causing a negligible effect on the stress-strain curves. However, the slope of the stress-strain curve from the volume-mesh model is reduced after the failure of the matrix, while the same slope obtained from the voxel model was stable with a small fluctuation. Due to the irregularity of the element generation, failure of the matrix may lead to more matrix element deletion compared with the voxel-mesh. Meanwhile, the step-like surface in the voxel-mesh may cause stress concentration, changing the distribution of the stress and increasing the difficulty of element deletion. A similar phenomenon can be observed in the tensile case, however, the strength of the unit cell is mainly determined by the fibre, so the effect of the step-like element on the strength is negligible.

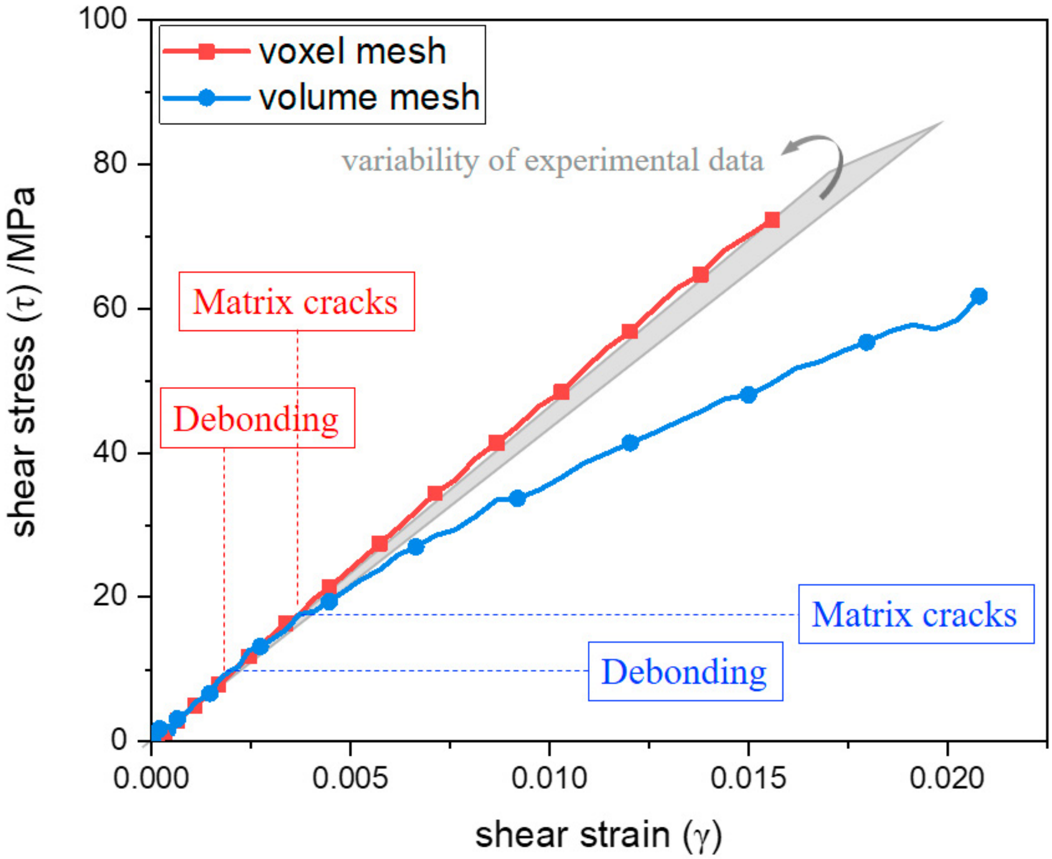


Fig. 3 Comparison of the experimental data (Ma *et al.*, 2019), with volume-mesh and voxel-mesh simulations about the shear behaviour

On the contrary, in the shear case, the step-like elements might affect simulation of the shear property, which is mainly determined by the matrix under the shear load. In brief, the matrix-element deletion of the volume-mesh model was severer than the voxel-mesh model, leading to an even lower strength. Considering the values and errors shown in Table 3, the strength prediction by from voxel-mesh shows better agreement with experimental results.

Table 3 Values from the experiments (Ma *et al*., 2019) and the numerical models (both volume- and voxel-mesh)

| | Experiment | Volume-mesh model | | Voxel-mesh model | |
|---|---|---|---|---|---|
| | | Value | Error/% | Value | Error |
| Tensile strength/MPa | 485.1(-35.50, +74.60) | 310.00 | -36% | 436.80 | -10% |
| Tensile Modulus/GPa | 28.4 (-4.18, +2.28) | 22.10 | -22% | 35.72 | +25% |
| Shear strength/MPa | 82.1 (-3.5, +3.5) | 61.80 | -24% | 72.3 | -12% |
| Shear modulus/GPa | 4.48 (-0.148, +0.148) | 4.73 | +5% | 4.73 | +5% |

## 4. Discussion

According to Fig. 2, Fig. 3 and Table 3, the elastic modulus simulated by the volume-mesh is closer to the experimental data than value predicted by the voxel-mesh model (if this value is considered at the beginning of the curve before the damage onset in the matrix ), but the predicted strength is always lower in the volume-mesh model than in the voxel-mesh model. However, the damage onset always occurs at a similar strain value, indicating that the deformation history in both models is comparable and the difference on the stress is caused by the mesh morphology or the element type. In the stress field under tensile loading, as shown in Fig. **4**, the stress distribution by these two models differs significantly. The stress gradient of the fibre with the voxel-mesh is smoother due to a better contact behaviour achieved by the step-like mesh on the contacting interface, which reinforces the importance of the contact interface. Stress oscillations during the mechanical response of the unit cell have been reported potentially due to step-like elements on the contact surface, especially on the fibre (Doitrand *et al*., 2015). However, this phenomenon was barely observed in the present study due to the simplicity of the loading condition. On the contrary, for the volume-mesh approach, the stress distribution of the fibre is in general more stable but the smooth distribution of the stress might be interrupted on the interface because of the contact effects, *i.e.* distortions of the contacting surface that provoke stress concentration on specific elements of the volume-mesh model as shown in Fig. 5. The stress concentration occurs at the end of the fibre, where the boundary condition is set. Additionally, the contact of the fibres can also cause this problem. As a result, in terms of the stress field, the voxel-mesh model seems to be more suitable to describe the stress field of the unit cell. However, when considering the similar damage location prediction, both mesh morphologies can provide good predictions of the damage onset.

The damage onset under the shear loading is also of interest. Fig. 6 presents the element deletion of the matrix in the shear simulation by the volume- and the voxel-mesh showing a similar matrix crack history in these two models. Region A and B are marked according to Fig. 6 which represents the poor-matrix region (region A), and the part with only the resin along the thickness of the unit cell, *i.e.* the rich-matrix region (region B). The failure process of both the voxel-mesh and volume-mesh model is included in Fig. 6 showing that the matrix cracking starts in the poor-matrix region (region A), propagates towards the rich-matrix region (from region A to region B), and finally ends joining the cracks from the boundaries, leading to the collapse of the structure. The shear loading was mainly carried by the matrix at the beginning, and the poor-matrix region is thus prone to fail because of the low shear strength of the epoxy with the thin cross-section. Subsequently the matrix cracks towards the rich-matrix region since that region has a high crack resistance due to the thick cross-section and the fact that the fibre provides no further structural reinforcement after the failure of the interface on another region. Finally, the cracks of the matrix join the cracks from the boundary that mimic possible cracks form another unit cell in the rich-matrix region based on the boundary conditions applied in the present simulated results. As a result, the rich-matrix region bridges the cracks initiated from the poor-matrix region until the whole structure of the composite collapses under the shear loads. Moreover, orthogonally symmetrical cracks can be observed in the unit cell, indicating the reliability of the boundary conditions.

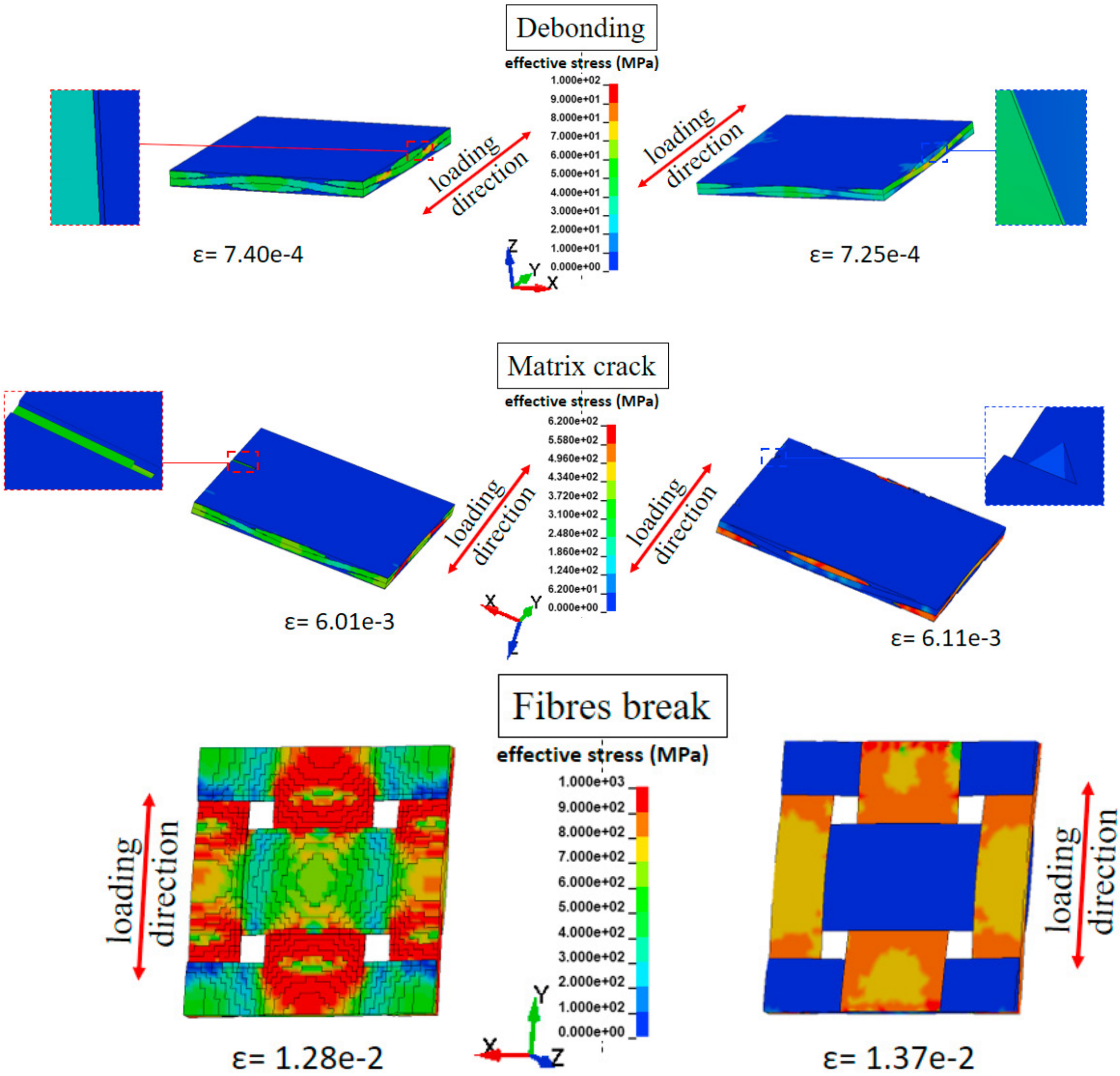


Fig. 4 Damage process from the voxel-mesh (left) and the volume-mesh (right) models in the tensile simulation

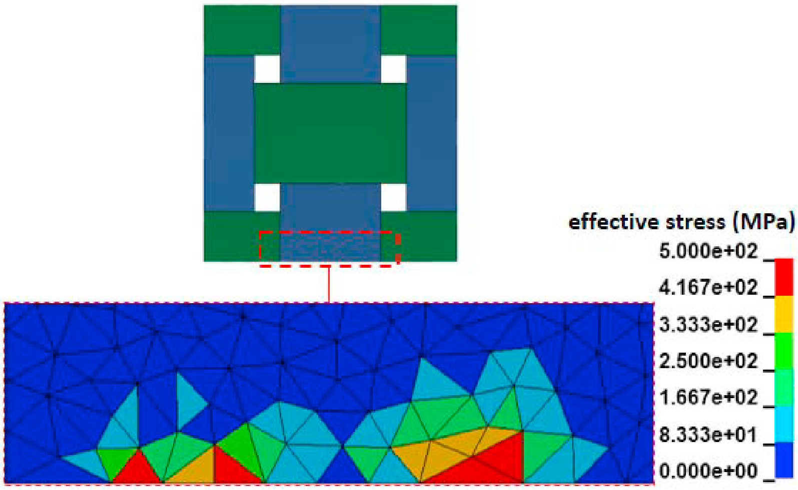


Fig. 5 The stress concentration phenomenon in the volume-mesh model

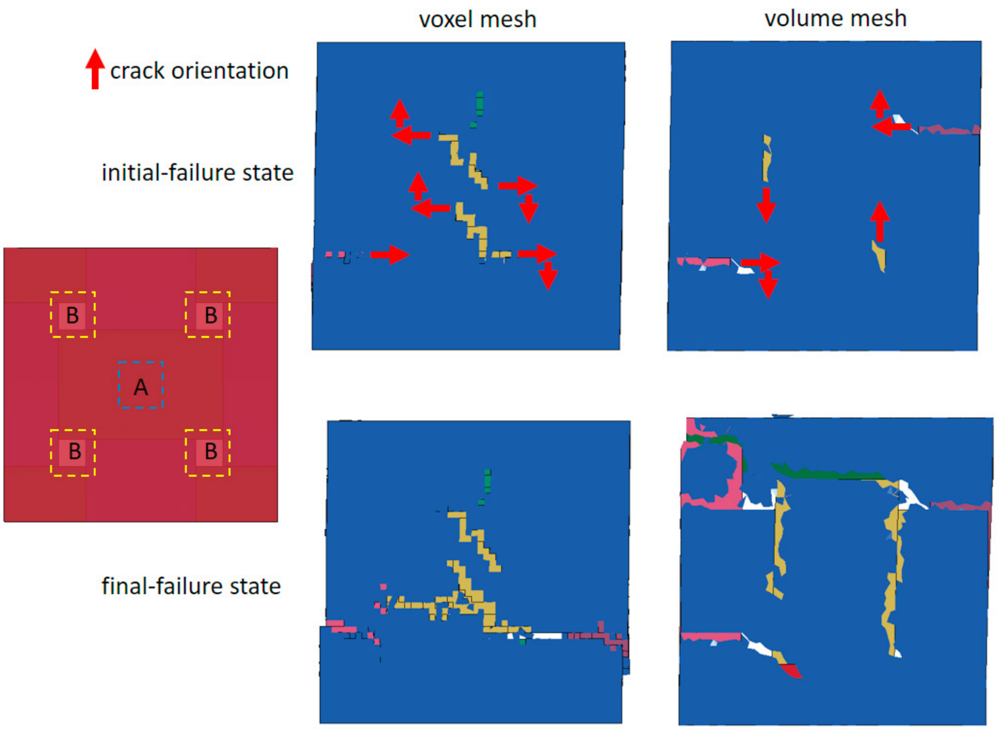


Fig. 6 Failure of the matrix from the voxel-mesh (left) and volume-mesh (right) models in the shear simulation

Regarding the distortion of the elements and the negative volume during the calculation, the distortion of the elements happens near the contact surface and the end of the fibre, leading to the stress concentration, as shown in Fig. 5. Moreover, a negative volume was found in the calculating process of the volume-mesh model. Considering the computational time, the volume-mesh model took 112 min while the highly efficient voxel-mesh model took only 53 min due to less element distortion and the occurrence of a negative volume. Additionally, in the simulation under shear loading, the use of limit strain is better than strength to control the element deletion for the volume-mesh, especially in the shear simulation. Changing the element deletion control might help to reduce the element distortion.

## 5. Conclusions

In the present work, both the volume-mesh and voxel-mesh mesoscale model were built in order to reproduce the mechanical behaviour of a composite RVE made of glass-fibre woven fibre with Epoxy Ampreg 26. Similar mesh sizes were considered to investigate the effect of the mesh morphologies on the simulation. A displacement-control loading was applied to create a stable stress state. The stress-strain curves from both mesh morphologies are acceptable compared with the experimental data, although the values predicted by the volume-mesh model are always lower. Regarding the damage process, the strain points predicted by both models for delamination, matrix crack and the failure of the fibre are the same, as reported in the literature (Doitrand *et al*., 2015; Zhao *et al*., 2019), indicating the reliability of both models. Subsequently, it was observed that the voxel-model shows a generally smoother distribution with regards to the stress field, although the step-like element geometry was found to be the possible reason for the stress oscillations, according to the work of Doitrand *et al.* (Doitrand *et al*., 2015). Moreover, the negative volume and element distortion increase the computational cost of the volume-mesh model.

The following conclusions can therefore be drawn:

- Both the volume-mesh and voxel-mesh models can provide acceptable stress-strain curves compared with experimental data, although the strength provided by volume-mesh model is always lower than by voxel-mesh model.
- The prediction of the damage process for the unit cell by both models is similar.
- The stress field provided by voxel-mesh is better in terms of the contact stress and less stress concentration, indicating this mesh morphology can achieve a more effective contact behaviour than the volume-mesh in the present stress state.
- Issues can be detected in the volume-mesh model, such as negative volume and element distortion, which reduce the computational efficiency.

In summary, we recommend using the voxel-mesh for engineering applications due to its straight forward preparation and high computational efficiency. However, for an in-depth understanding of the mechanism of the composite, the volume-mesh is better as a more accurate structure can be guaranteed and a detailed damage process can be obtained. However, the focus should be put on the solution of the contact problem and the geometry distortion, additional to the generation of the mesh morphology.

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