MICROMECHANICAL PROGRESSIVE DAMAGE MODEL FOR PREDICTING RESIN DOMINATED STRENGTH VALUES OF FIBRE REINFORCED COMPOSITES UNDER VARIOUS TYPES OF LOADING

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Abstract

In this study, a three-dimensional (3D) hexagonally packed representative volume element (RVE) is used to investigate the mechanical behaviour of AS4/8552 under various types of loading. Firstly, elastic properties of the composite are predicted with Finite Element Based Micromechanics (FEBM) method. Secondly, residual stress development in the composite throughout its cure cycle is simulated. Finally, progressive damage assessment of AS4/8552 is carried out under resin dominated loading modes with respect to Maximum Principal Stress, Raghava's and Bauwen's Modified von-Misses failure criteria. Predictions are compared to experimental results and a good correlation is observed.

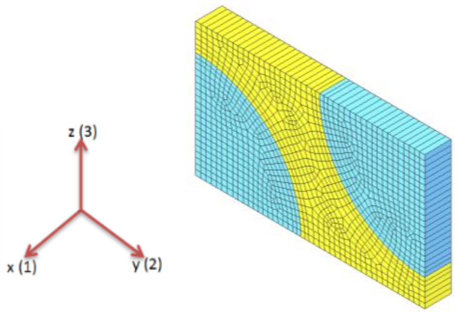
1 Introduction

Micromechanical analysis of composites has been very popular in recent years. There are several types of methods in the literature. Finite Elements (FE) is one of the most important one. The overall behaviour of a composite can be predicted by using micromechanics approach, namely, by modelling the composite in its constituents' level. It is assumed that the fibres lie inside the matrix in square and hexagonally packed arrays which represent the composite correctly and they are called representative volume elements (RVE). Nedele and Wisnom [1] examined the simultaneous thermal and shear loading of a unidirectional composite with FE micromechanical analysis by a 3D quarter square packed RVE. Akzo HTA carbon fibre and Ciba-Geigy F922 epoxy matrix are tested. They found that the shear modulus of resin has important effect on the shear moduli of the composite but the maximum shear stress in the matrix is not affected as much as the moduli. Sun and Vaidya [2] predicted the properties of AS4/3501-6 with FE micromechanics approach. They used 3D RVEs to predict elastic moduli. Transverse shear modulus was obtained by a 2D square-packed whole RVE and longitudinal shear modulus was predicted with a 3D whole square-packed RVE. The modulus was obtained by dividing the average stress to the average strain in regarding direction which were calculated by using the strain energy equivalence principle to relate the energy stored in the RVE to the external work done on it. Chen, Xia and Ellyin [3] investigated the effect of viscoelasticity of matrix on the evolution of residual stress during cooling by FE micromechanics method. They used a 3D square packed RVE. It was seen that higher cooling rates results in higher residual stresses in the resin. Elastic resin accumulates higher residual stress than viscoelastic resin. Further investigation with the same material was carried out by Zhao, Warrior and Long [4] with 2D square packed RVEs. Quarter and whole RVEs were used for transverse tensile and shear loadings respectively. Effect of residual stress was investigated. Material properties of resin were assumed as elastic and temperature-dependent. Maximum Principal Stress criterion with element stiffness degradation technique was used for failure assessment. It was found that damage pattern was highly affected with the presence of residual stress which causes beneficial consequences for transverse tensile loading and detrimental consequences for transverse shear loading. Same authors [5] repeated the same study for longitudinal shear, longitudinal and transverse normal loadings for the same materials with viscoelastic resin by different types of RVE to investigate the effect of fibre packing geometry with different fibre volume fractions. Maligno developed Zhao *et. al*'s study with hexagonally packed RVEs in his PhD thesis [6]. First, moduli of an E-Glass fibre/epoxy matrix for different fibre volume fractions were obtained, then residual stresses induced in E-Glass/MY750/HY917/DY063 epoxy composite due to cooling was investigated. Afterwards, damage progression under transverse tensile loading was examined with respect to maximum principal stress and Raghava's modified von Misses (MVM) failure criteria with and without the effect of residual stress. Ernst *et al.* [7] carried out a multi-scale failure analysis for a textile composite. Moduli of composite were predicted by using square and hexagonally packed RVEs. Resin was modelled as an elasto-plastic material. At the end of the study it was found that the experimental and predicted moduli and strength values are very close to each other which proved the success of the model and approach. Effect of residual stress was not included in Ernst's study. So it was stated that modelling the resin as an elasto-plastic material without the effect of residual stress is appropriate for micromechanical analysis of glass fibre/epoxy composites. Ersoy *et. al.* [8] calculated the physical and mechanical properties of AS4/8552 through cure by using Finite Element Based Micromechanics (FEBM) and an analytical approach. A hexagonally packed RVE was considered for FEBM. Calculated glassy moduli were compared to experimental values and they are reasonably close to each other. This study is a further improvement of Ersoy *et. al's* study [8]. Its main goal is to develop a micromechanical model by using a FE method with ABAQUS/Standard to predict mechanical behaviour of AS4/8552 and assess the damage progression under resin dominated loading modes, by taking into account the effect of residual stress. Residual stress is modelled by implementing the instantaneous strain and temperature dependent properties of resin through its cure cycle into the model by using ABAQUS user defined subroutine UMAT. Progressive damage behaviour is modelled with another user defined subroutine, USDFLD. Predicted values are presented and compared to experimental results.

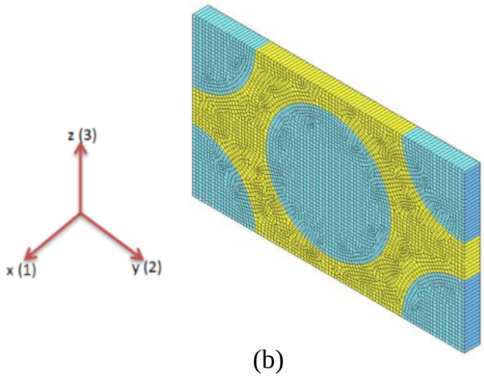
2 Finite Element Analysis

2.1 Representative Volume Element

A 3D hexagonally packed RVE is selected in this study. 20 nodded brick elements (C3D20) are used to mesh the model. Results converge when the element size is less than or equal to 0.0002 mm. RVEs with 0.0002 mm element size are shown in Figure 1 where fibres and resin are represented with blue and yellow sections respectively. Regardless of the volume fraction, dimensions of the RVE should follow the parameters of the hexagon geometry. The ratio of the sides of the RVE should be $\sqrt{3}$ and the thickness of the element is chosen as 0.001 mm. In FE model, boundary conditions (BCs) are very important for periodicity and symmetry of RVE. BC for normal and thermal loading are given in Table 1.a. Nodes on x=0, y=0 and z=0 planes are restricted (R) to move in their normal direction but they are free (F) to move in perpendicular directions and to keep the edges planar after deformation, nodes on opposite surfaces are constrained (C) to move the same amount in normal directions. BCs for longitudinal shear loading are given in Table 1.b. For subsequent longitudinal shear loading after the cure cycle, BCs should be modified. During cure cycle, BCs in Table 1.a should be applied and then it should be switched to Table 1.b. Quarter RVE does not enable to model transverse shear loading, so a whole RVE as in Figure 1.b is used. The origin of the model is the mid-node of the RVE and it is restrained in all directions. All nodes are restrained to move in fibre direction and the equation constraints applied for top and bottoms planes in y-direction and left and right planes in z-direction are presented in Equations 1 and 2.



(a)



(b)

Figure 1.a. Quarter **b.** Whole hexagonally packed RVE with Cartesian coordinate system.

$$u_y(TOP) + u_y(BOTTOM) = 0 \tag{1}$$

$$u_z(LEFT) + u_z(RIGHT) = 0 \tag{2}$$

PLANE	X	Y	Z
x=0	R	F	F
x=1	C	F	F
y=0	F	R	F
$y = L\sqrt{3}$	F	C	F
z=0	F	F	R
z=L	F	F	C

(a)

PLANE	X	Y	Z
x=0	F	R	R
x=1	F	R	R
y=0	R	R	R
$y = L\sqrt{3}$	F	R	R
z=0	F	R	R
z=L	F	R	R

(b)

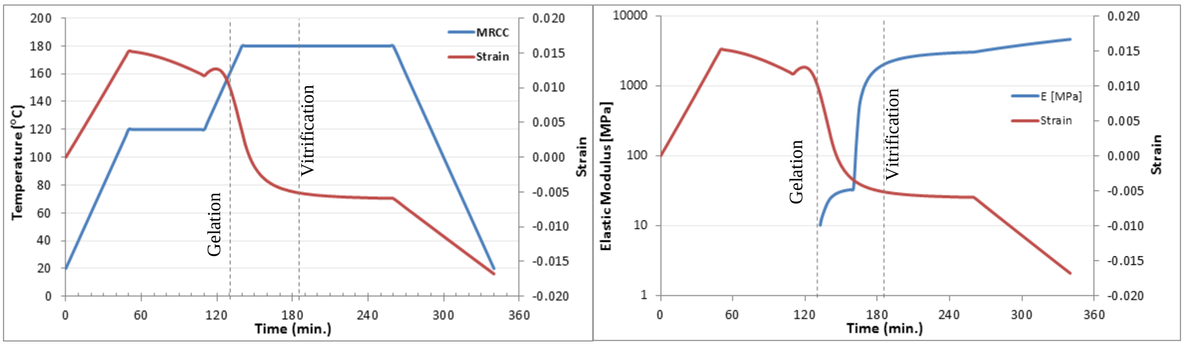
Table 1. Boundary conditions for **a.** Normal & Thermal loading **b.** Longitudinal Shear Loading

2.2 Prediction of Elastic Moduli

Elastic properties of AS4/8552 with 57.4% V_f are predicted with $L = 0.0050278$ mm and $L\sqrt{3} = 0.008708$ mm. Constituents' properties can be found in [8,11]. Unit load is applied in the direction of concern and it is divided to the strain in that direction to calculate the modulus.

2.3 Prediction of thermochemical strains and residual stresses

Residual stress developing in a unidirectional AS4/8552 ply throughout the Manufacturer's Recommended Cure Cycle (MRCC) described in [11] is investigated. Previously, Ersoy et al [8] predicted the development of thermochemical strains and elastic modulus of the resin as the cure progresses by using Group Interaction Modelling (GIM) as seen in Figures 2.a and b respectively. Gelation point of the composite is the 130th min. of the cure cycle. Vitrification point is 45 minutes after 180 °C dwell begins [8]. Development of thermochemical strains and the modulus of the resin are modelled by UMAT. Residual stress induced in composite is calculated using equation 3 for resin.



(a) (b)

Figure 2.a. Temperature and linear thermochemical strain of 8552 resin throughout MRCC. **b.** Development of elastic modulus and strain of 8552 resin throughout MRCC.

$$\{DSTRESS(i,j)\} = [C]\cdot\{DSTRAN(i,j) - \delta_{ij}\cdot d\varepsilon_{th}\} \tag{3}$$

in which [C] is the stiffness matrix, the array of incremental stress and mechanical strain are represented with DSTRESS(i,j) and DSTRAN(i,j) respectively and $\delta_{ij}\cdot d\varepsilon_{ij}$ is the incremental strain change due to chemical and/or thermal effects during MRCC.

2.4 Progressive Failure Analysis

Progressive failure is modelled with stiffness reduction method in conjunction with ABAQUS user defined subroutines USDFLD and UMAT as in [4,6]. Failure behaviour of AS4/8552 is investigated with respect to Maximum Principal, Raghava's and Bauwen's MVM criteria under various types of loading with and without residual stress. Details of these criteria can be found in [6]. Resin dominated load cases are investigated. Strength values of resin are required. Tensile strength of 8552 resin is available in [11], but the compression strength is not. Compression strength of 3501-6 epoxy resin is known as 250 MPa, and same compressive strength/tensile strength ratio is assumed to be valid for 8552 epoxy resin which gives a compressive strength of 300 MPa for 8552 resin. The interfacial adhesive strength properties are assumed to be equal to cohesive strength of the resin.

3 Results and Discussion

3.1 Elastic Moduli Prediction

Deformations under each load case to predict elastic moduli are given in Figure 3. Predictions for elastic moduli for AS4/8552 are given in Table 2 and they show very good agreement when compared to previously found experimental and numerical values.

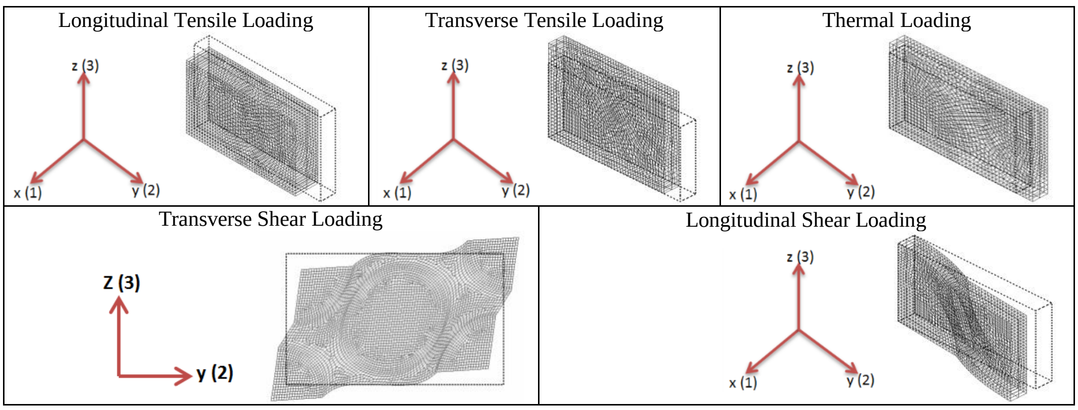


Figure 3. Deformations under various loading cases.

Properties	FEBM [8]	Measurement [13]		This Study		
E_1	134000	129000^T	113200^C	133000		MPa
E_2=E_3	9480	9050^T	9850^C	9755		MPa
G_{12}=G_{13}	5490	4830		5228		MPa
G_{23}	3272	-		3194^f	3194^{TI}	MPa
ν_{12}=ν_{13}	0.271	0.302^T	0.335^C	0.267		-
ν_{21}	-	0.029		0.0196		-
ν_{23}	0.448	0.45		0.527		-
α_1	-	-		0.232		x 10^{-6}/°C
α_2=α_3	40	32.6		40.03		x 10^{-6}/°C

^{T}: Tension – ^{C}: Compression – ^{f}: Full RVE Model – ^{TI}: Transverse Isotropy

Table 2. Comparison of results for AS4/8552 (V_f=0.57)

3.2. Cure Shrinkage and Residual Stress Analysis

Incremental strain in transverse directions during MRCC simulation is plotted in Figure 4. It is very similar to Figure 2. Coefficients of thermal expansion (CTE) in each direction are calculated during cooling from 180 °C to 20 °C and presented in Table 3. Maximum of 67 MPa tensile and 47.5 MPa compressive residual stresses are induced in resin and fibres respectively in the fibre direction as seen in Figure 5.a. According to the V_f of the composite, they balance each other. Figure 5.b shows the stress induced in fibre direction in resin at a more sensitive scale at the end of the cure cycle.

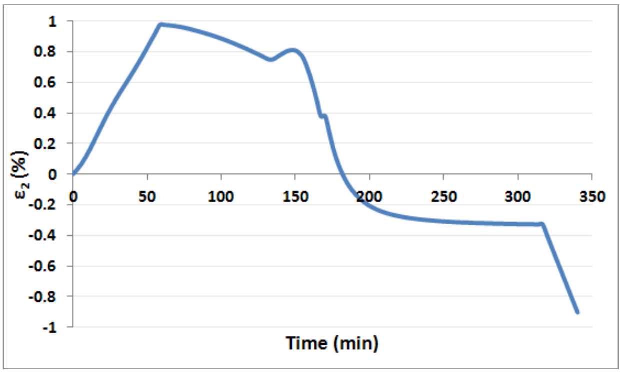


Figure 4. Variation of strain in transverse directions during cure cycle.

CTE	Present Study	[13]
α_1 (10^{-6} /°C)	1.01	-
α_2=α_3 (10^{-6} /°C)	35.6	32.6

Table 3. CTE of AS4/8552.

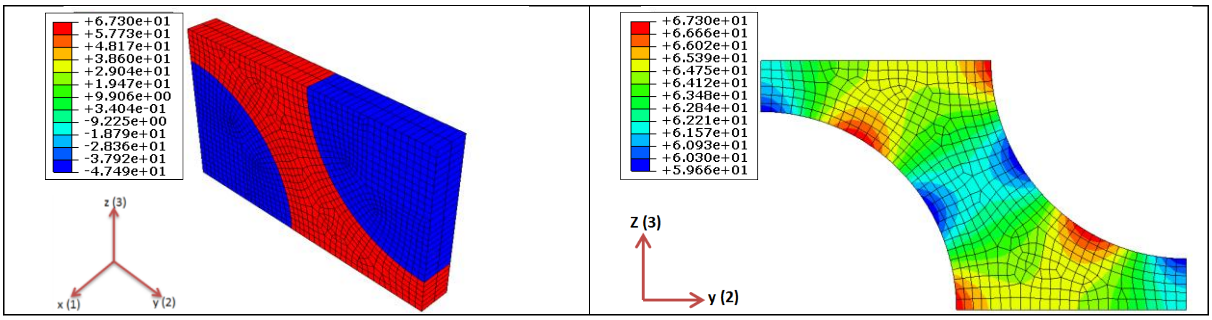


Figure 5.a. Stress induced in fibre direction in composite. **b.** Stress induced in fibre direction in resin (t_{end}).

CTE values are different in Tables 2 and 3. In Table 2, effect of modulus change during cooling is not taken into account, only glassy properties are used but in Table 4, thermo-mechanical properties from GIM [8] are considered. So, different values are obtained.

3.3. Progressive Damage Assessment

Only the details of damage path under transverse tensile loading are sketched. Figures 6, 7 and 8 present the damage paths with respect to maximum principal, Raghava's and Bauwen's MVM respectively. Residual stress and failure criteria highly affect the damage progression.

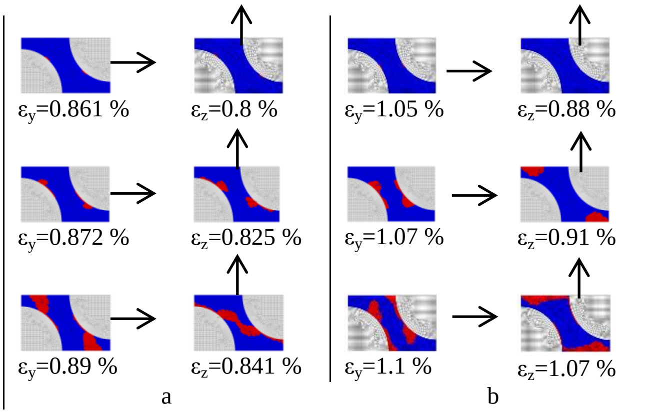


Figure 6. Damage progression under transverse tensile loading with respect to Maximum Principal Stress failure criterion a. with residual stress; b. without residual stress

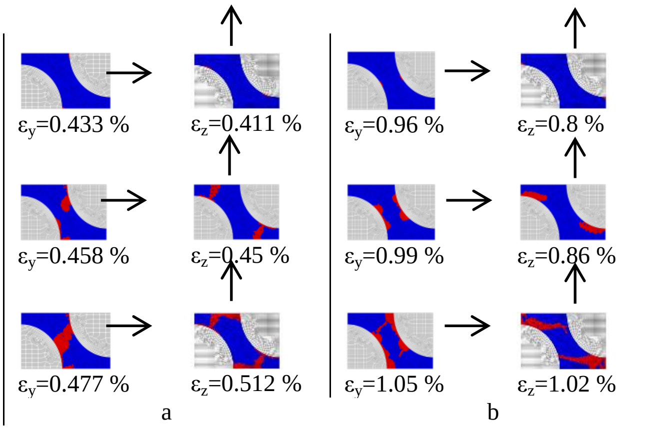


Figure 7. Damage progression under transverse tensile loading with respect to Raghava's MVM failure criterion a. with residual stress; b. without residual stress

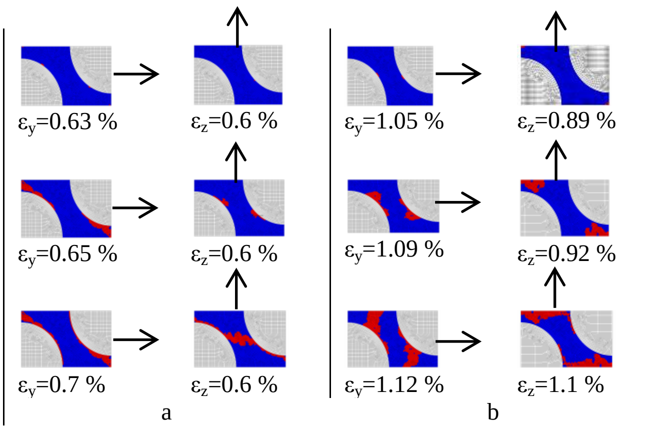


Figure 8. Damage progression under transverse tensile loading with respect to Bauwen's MVM failure criterion a. with residual stress; b. without residual stress

The comparison of transverse tensile strength values for AS4/8552 is given in Table 4 and plotted in Figure 9 for every failure criteria with presence of residual stress. It is noticed that the difference between the strength values predicted by each failure criteria and loading direction is high. That was not the case for glass-reinforced composite, probably because the isotropic properties of the glass fibres. The comparison of transverse compressive strength of AS4/8552 is given in Table 5. Residual stress does not influence the damage progression under transverse compression with respect to Maximum Principal Stress criterion as contrary to Raghava's and Bauwen's MVM failure criteria. It is also very similar for all situations under longitudinal shear loading. Longitudinal shear strength values are given in Table 6.

[MPa]	With Residual Stress		Without Residual Stress	
	σ_y^T	σ_z^T	σ_y^T	σ_z^T
Max. Princ.	83.9	77.6	102.2	85.2
Raghava	42.1	39.7	93	77
Bauwen	61.5	57.8	103.3	86.3
[13]	63.0 (STD = 5.982)			

Table 4. Comparison of transverse tensile strength of AS4/8552.

[MPa]	With Residual Stress		Without Residual Stress	
	σ_y^C [MPa]	σ_z^C [MPa]	σ_y^C [MPa]	σ_z^C [MPa]
Max. Princ.	250	200.6	255.4	213.4
Raghava	216.8	244.8	292.1	323
Bauwen	190.2	232.6	263.3	326.5
[13]	267.0 (STD = 6.276)			

Table 5. Comparison of transverse compressive strength of AS4/8552.

[MPa]	τ_{yz}^S (With Residual Stress)	τ_{yz}^S (Without Residual Stress)
Max. Princ.	73.4	100.3
Raghava	49.5	93
Bauwen	47.4	83
[13]	55.0 [0.2 % offset] (STD = 1.654)	

Table 6. Comparison of longitudinal shear strength of AS4/8552.

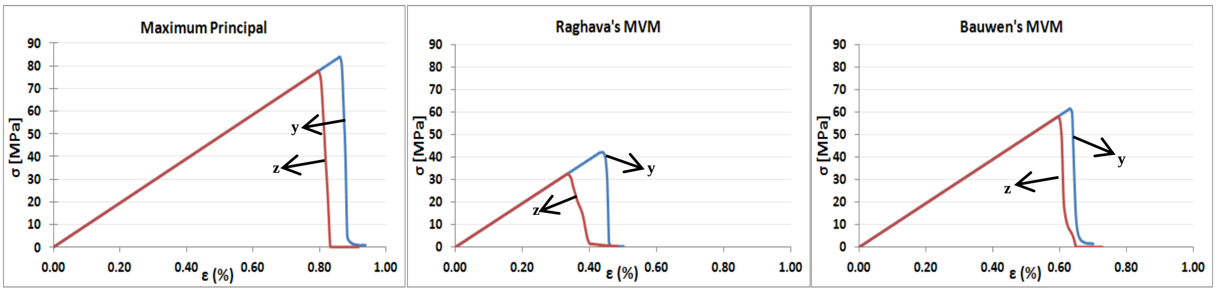


Figure 9. Global stress-strain curve under transverse tensile loading including the effect of residual stress

Results indicate that, disregarding the effect of process-induced residual stresses causes an over-prediction of strength values. A least square difference method where the average sum of squares of the difference between the predicted and the measured values are compared is used that takes into account all loading modes. By considering the predictions with residual stress, maximum principal stress seems to be the most suitable criterion for strength prediction.

4 Conclusion

A hexagonally packed RVE is developed for calculating the elastic moduli, modelling the MRCC for detailed residual stress analysis and progressive damage assessment of AS4/8552. It is seen that, the model developed within this study is a good method for predicting mechanical behaviour of polymeric composites when experimental study is difficult to perform or relevant data are not sufficient. It is also seen that, hexagonally packed RVE gives close predictions but it is affected with loading direction for failure assessment.

5. Acknowledgements

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