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The effect of microstructure of unidirectional fibre-reinforced composites on mechanical properties under transverse loading: A review

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ABSTRACT

Unidirectional Fibre-Reinforced Composites (UD FRCs) are increasingly used in the sectors of aerospace, automotive, construction, marine and other technical applications over the decades due to their low weight, high mechanical, thermal properties and high corrosion resistance etc. As a result, the understanding of mechanisms of their fracture and failure under different loads especially under transverse loading are very important in order to take full advantage of their excellent performance, to optimise production procedures and to develop new materials with higher performance. This paper reviewed the effects of the microstructure of a composite material (including fibre volume, fibre distribution, bonding quality between fibres and matrix, and characteristics of matrix) on the performance of FRP composites according to mechanics theories and finite element method (FEM) for microstructure analysis.

Keywords: Fibre reinforced composite, transverse tension and shear, microstructure, FEA

1 Introduction

Unidirectional Fibre-Reinforced Composites (UD FRCs) has high mechanical strength, but the strength under transverse tension is much smaller than that of under longitudinal tension [1] mainly due to the lack of fibre strength in the transverse direction. For unidirectional fibre composites, Barley et al. [2] summarized that the low transverse tensile strength is a major weakness of composites and the presence of fibres results in stress concentrations and the strength is lower than that of the unreinforced matrix in transverse direction.

Therefore, the investigation on mechanical properties, fracture and failure of FRC under transverse loading becomes a very important research topic. Traditionally, elasticity mechanics were often used to predict the failure of composite materials. With the development and application of Finite Element Analysis (FEA) as an analytical tool in mechanics and heat transfer analysis in the last several decades, FEA modelling becomes dominantly used for understanding the performance of composite materials as the model provides detailed and visible engineering information such as stress/strain, deformation, natural frequencies, etc. about a composite material which is difficult to obtain from traditional analysis methods.

Many researchers [3, 4, 5, 6,7] have reported that transverse tensile loading can cause significant stress concentration and the maximum principal stress in the matrix is along the direction of loading.

Apart from the stress concentration induced by fibres, the adhesion between matrix and fibre, the matrix mechanical properties and the void inside the matrix can also affect the fracture and failure of UD FRP composites.

Main factors affect the strength of unidirectional composite under transverse tension include:

1. Fibre parameters including the fibre diameters, fibre volume fraction, fibre distribution, fibre array and fibre spacing play key roles in determining the strength of UD FRC.
2. Matrix mechanical properties, matrix shrinkage and voids parameters including shape, volume and distribution in the matrix.
3. Adhesion between fibre and matrix including fibre preparation before production and molecular absorption between each other.
4. Different mechanical and thermal properties between matrix and fibre.

The possible local failure modes can happen include the following as Nachiketa concluded [3]:

- Matrix cracking
- Interface debonding
- Fibre splitting transversely

It has been shown in many papers that the fracture mechanisms of UD FRC differ as dominant factors vary. The research in the failure of UD FRCs always targeted on two parts- the origin of the facture and how the crack is propagated. In general, there are three methods to model the composite material [8, 9, 10, 11]:

Microscale analysis: This method focuses on the local constituents (fibre, matrix, and interface) Periodicity can be applied in this method.

Macroscale analysis: This method applies homogenized material properties of the composite on global composite structure.

Mesoscale analysis: This method applies microscale model for all directions which may not periodic.

In all three methods, microscale analysis is the most applied method for analysing fracture and failure for UD FRC materials as the fibres can be represented by circles in 2D model and cylinder in 3D model at transverse section of the material. This represented model is called unit cell model or RVE (Representative Volume Element) model. It is the most convenient form in the micromechanical analysis. In general, the microscale model has three constituents including the fibre, the matrix and the interface between each other, or two constituents including the fibre and the matrix. The interface between fibre and matrix is modelled by failure criteria based contacts.

The research for the effect of composite microstructure on composite fracture and failure under transverse loading is reviewed in details below under three sections: The fibre, the matrix and the interface.

2 The effect of composite microstructure on composite fracture and failure under transverse loading

2.1 The fibre

Fibre characteristics include fibre nature, fibre diameters, fibre volume fraction, fibre distribution, fibre array and fibre spacing. These properties all have influence in transverse tensile strength. The research on how fibre affects the mechanical properties of composite material under transverse loading has been extensively researched experimentally [12,13,14,15] and theoretically [4,5,16,17,18,19,20,21,22].

The earliest study applying unit cell was carried out by the pioneering work at that time from Adams and Doner [21]. The model was established by utilising periodic square array of elastic fibres contained in an elastic matrix and subjected to a transverse load. Finite difference representation of the governing equilibrium and stress-displacement equations were applied. In their study, the filament (fibre) in the composite was subjected to normal stress perpendicular to the direction of filament axis with uniform temperature. The matrix and the fibres were perfectly bonded to each other. Various fibre cross-sectional shapes (circular, elliptical), a range of filament spacings, fibre volume and matrix properties were utilised. The numeral results were compared with experimental data. The results of the effect of fibre volume on the maximum principal stress versus the constituent stiffness ratio (E_f/E_m, modulus ratio of fibre and matrix) based on the fibre square array under transverse tension are shown in Fig. 1. It can be seen that normalised maximum principal stress increases with the increase of modulus ratio of fibre and matrix and stabilise at a certain point depending on the fibre volume and filament spacing. It also increases with the fibre volume. This means that it is easier to initiate a crack in a matrix with higher modulus ratio of fibre to matrix, and with higher fibre volume. It can also be seen that when the fibre volume is more than 70%, stress concentration increases much faster with the increase of fibre volume.

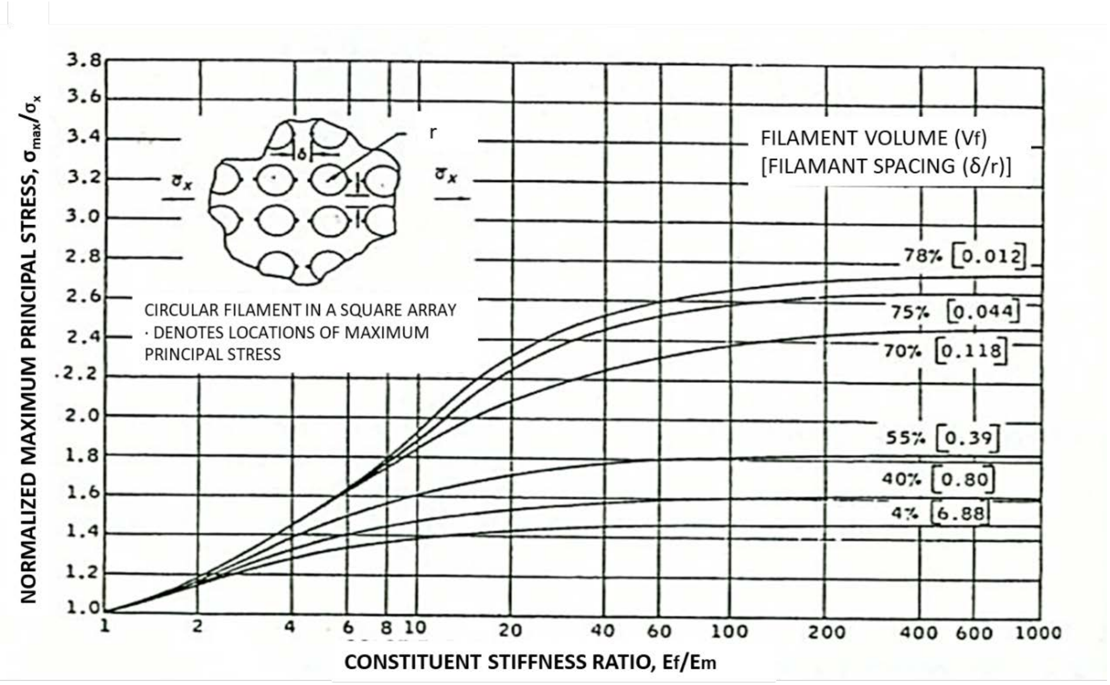


Fig. 1. The effect of modulus ratio of fibre and matrix and fibre volume on stress concentration (Adams and Doner, 1967[21]).

Adams and Tsai [22] continued the work on comparing regular fibre array geometries (square regular arrays and hexagonal regular arrays, Fig. 2)and random array geometries (square random arrays and hexagonal random arrays, Fig. 3 and Fig. 4)on the stress values. It was concluded that the more physically realistic hexagonal random array model provides better agreement with experimental data than the random square array model (Fig. 4) which is in contrast to that regular square model has better agreement with the experimental results (Fig. 2).

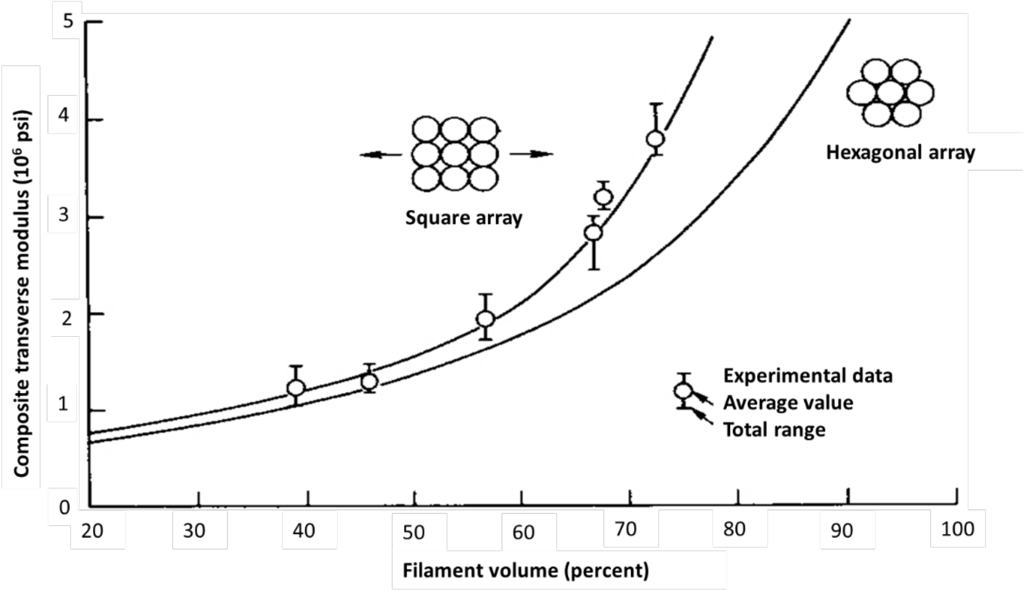


Fig. 2. Square and hexagonal regular random array analysis and experimental data: glass-epoxy composite-. (Adams and TSai, 1969)[22]

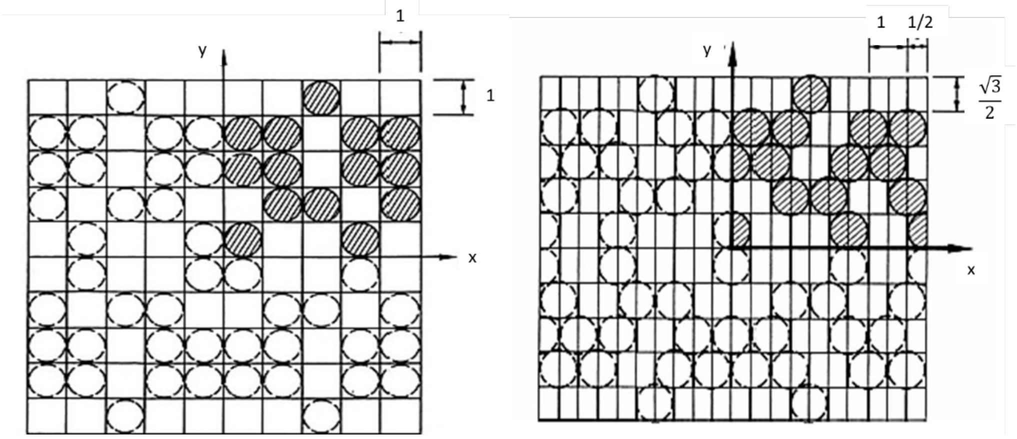
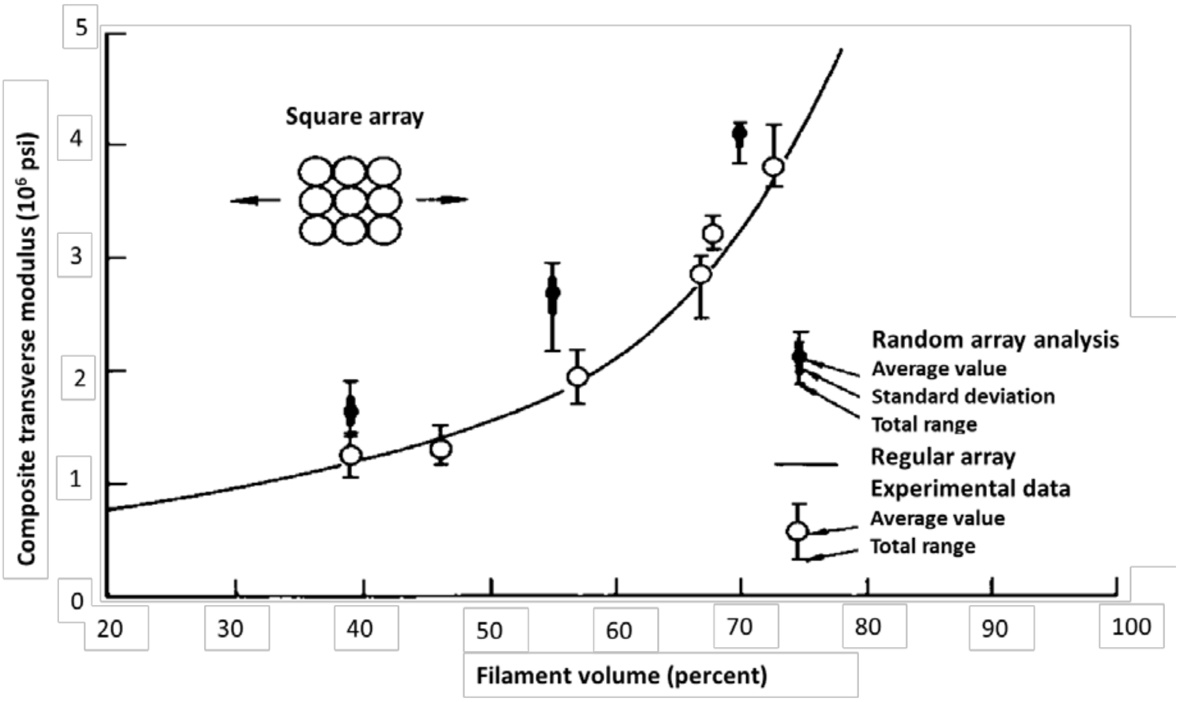


Fig. 3. Square random arrays and hexagonal random arrays Adams and Tsai (1969) [22]



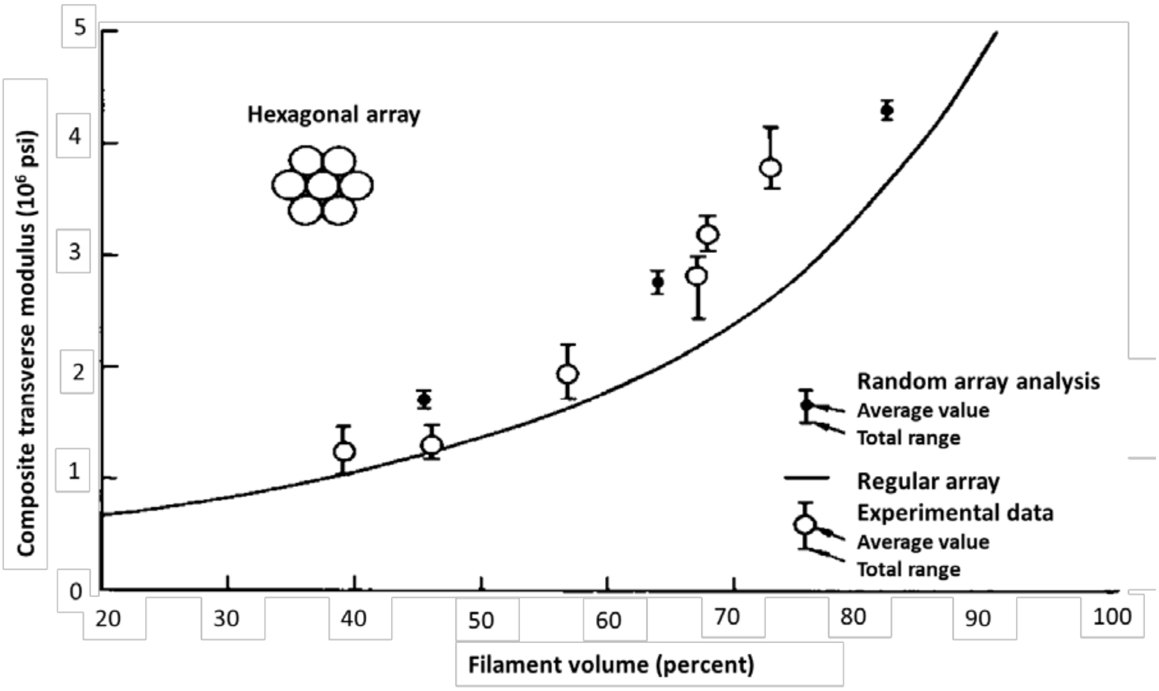


Fig. 4. Square and hexagonal random array analysis: glass-epoxy composite-comparisons with hexagonal regular array analysis and experimental data. (Adams and TSai, 1969)[22]

After that, extensively microscopic studies are carried out based on square array [5,23,24] and hexagonal array[25,26,27,28,29]. Among these researches Li [5] introduced unit cell model of regular packing but with cross-sectional irregularities such as local cracking and debonding etc. This unit cell model also allows arbitrary combinations of macroscopic stresses or strains to be applied as the loads to the unit cell without having to change to different sets of boundary conditions [5]. The procedure of processing the results from a micromechanical analysis is simplified greatly.

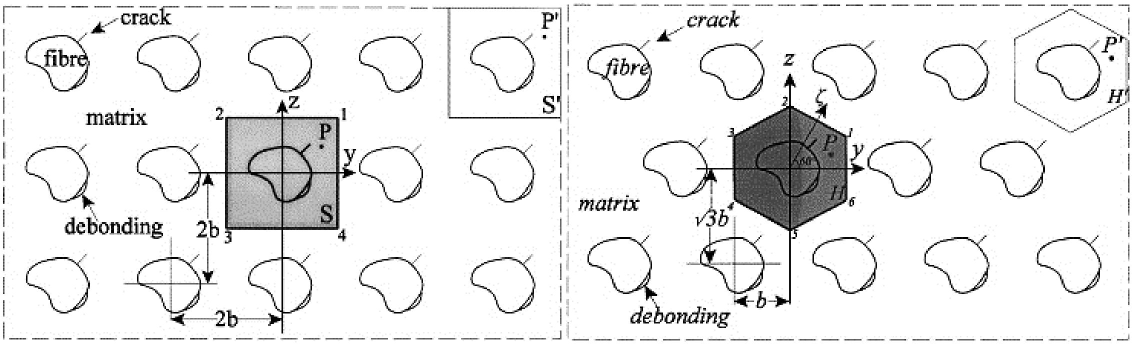
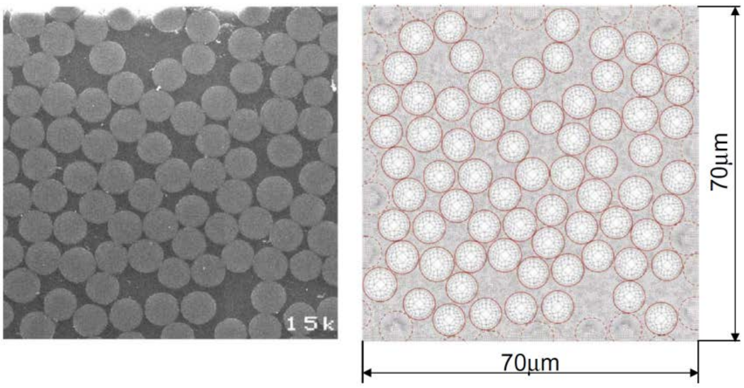


Fig. 5 Square packing and square unit cell (left); Hexagonal packing and hexagonal unit cell (right). (Li, 2001) [5]

Apart from FE method which is utilized to analyze the stress and strain for UD FRC under transverse loading, Volume Integral Equation Method (VIEM) is also introduced for the solution of elastostatic problems in unbounded isotropic elastic solid containing interacting multiple isotropic and anisotropic circular/elliptical inclusions subject to remote antiplane shear. This method is applied to two-dimensional problems involving long parallel cylindrical inclusions (fibres). In recent volume integral equation method (VIEM)work done by Lee, J. K. (2012)[30] , a detailed analysis of the stress field at the interface between the matrix and the inclusions is carried out for square and hexagonal packing of isotropic and anisotropic inclusions subject to remote antiplane shear. The author compared the interaction effect of square and hexagonal arrays of isotropic and orthotropic circular/elliptical inclusions on the shear stress component and the normalized shear stress component at the interface. It was concluded that the VIEM is highly accurate and effective for investigating stresses in composites containing arbitrary geometry and multiple anisotropic inclusions [30].

In order to improve the model for better correlation with the experimental results and real world situation, fibre array random distribution has been implemented in considerable work later on in computational modelling of the transverse behaviour of UD FRC[21,28,31,32,33,34,35,36,37,38]. The random geometry distribution can be implemented mainly by two approaches: One is based on composite's observed microstructure, such as the work done by Hojo (2009) [10] as shown in Fig.6. Hojo et al have carried out a detailed investigation to determine the effect of local fibre array irregularities on the microscopic interfacial normal stress (INS) states for thermally and transversely loaded CF/epoxy. It was found that INSs are controlled by the fibre distribution parameters such as the inter fibre length (fibre spacing) and the fibre alignment angle. The results are shown in Fig. 7.



(a) Original scanning electron micrograph (b) Image-based FE mesh for Model 1

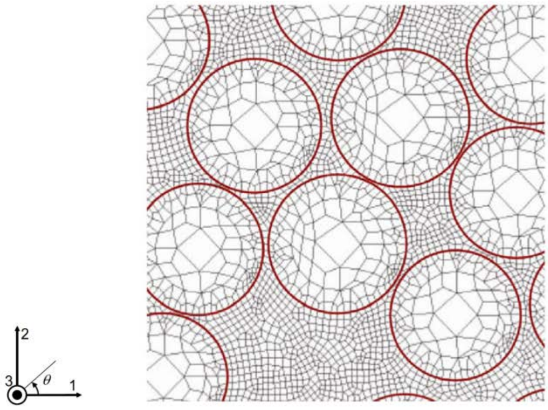


Fig. 6, Composite's observed microstructure model (Hojo, 2009) [10]

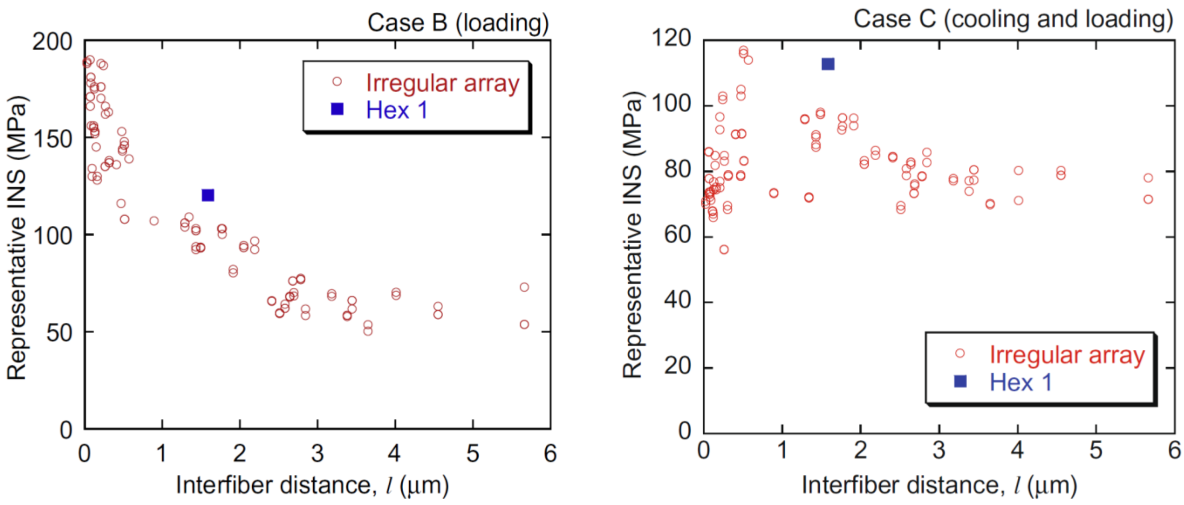


Fig. 7, Relation between representative INS and interfibre distance for Case B (loading) and Case C (cooling and loading) (Hojo, 2009)[10]

But as reviewed in Bulsara's work [39] that the FEA model created by this method can only present one local microstructure, it is not representative to the whole composite microstructure. It was also reported that the procedure could be costly and time consuming [39]. Thus, another option proposed in the work Yang et al. [40] is to create the model with extreme conditions such as fibre rich and matrix rich area. Random fibre distribution, matrix plastic deformation and interfacial debonding were all considered in this paper. The results show that the transverse shear failure of the composite is dominated by matrix plastic damage, while the in-plane shear failure of the composite is initiated by interfacial debonding and then dominated by matrix damage. The results again confirmed that the fibre distribution has great influence on the fracture and crack propagation especially in transverse loading.

Wongsto and Li [41] continued to investigate the effect of randomly distributed fibres on composite mechanical properties in micromechanical FE analysis using ABAQUS. They applied random angle between 0 and 360degree to determine the direction for the fibres to locate. The distance is determined by kρ where random number k is generated between 0 and 1 and ρ is the maximum distance can be located. The scheme is shown in Fig. 8 and the random fibre distribution obtained after certain iterations are shown in Fig. 9. The results from this paper show that the predicted transverse Young's and shear moduli from UD composites FE models with fibres distributed at random over the transverse cross section correlated better with experimental results and theoretical results and the values are higher than those obtained with regular packed fibres. It also concluded that the benefit of applying random distribution of fibres also increase the strain hardening of the material in the plastic regime when the fibres is subjected to transverse loading. This phenomenon cannot be predicted from models with a regularly packed fibre arrangement.

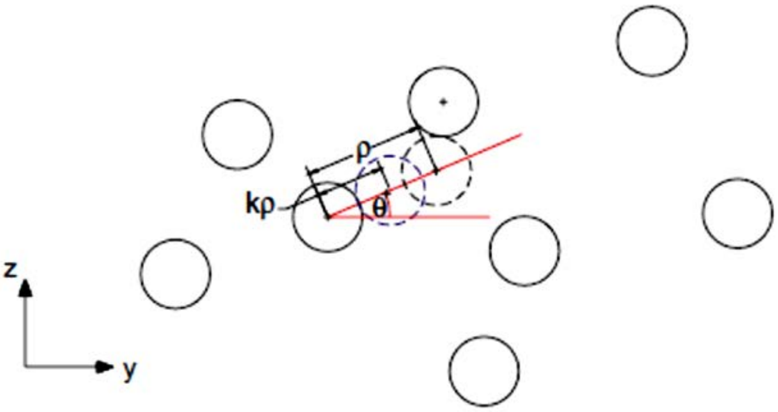
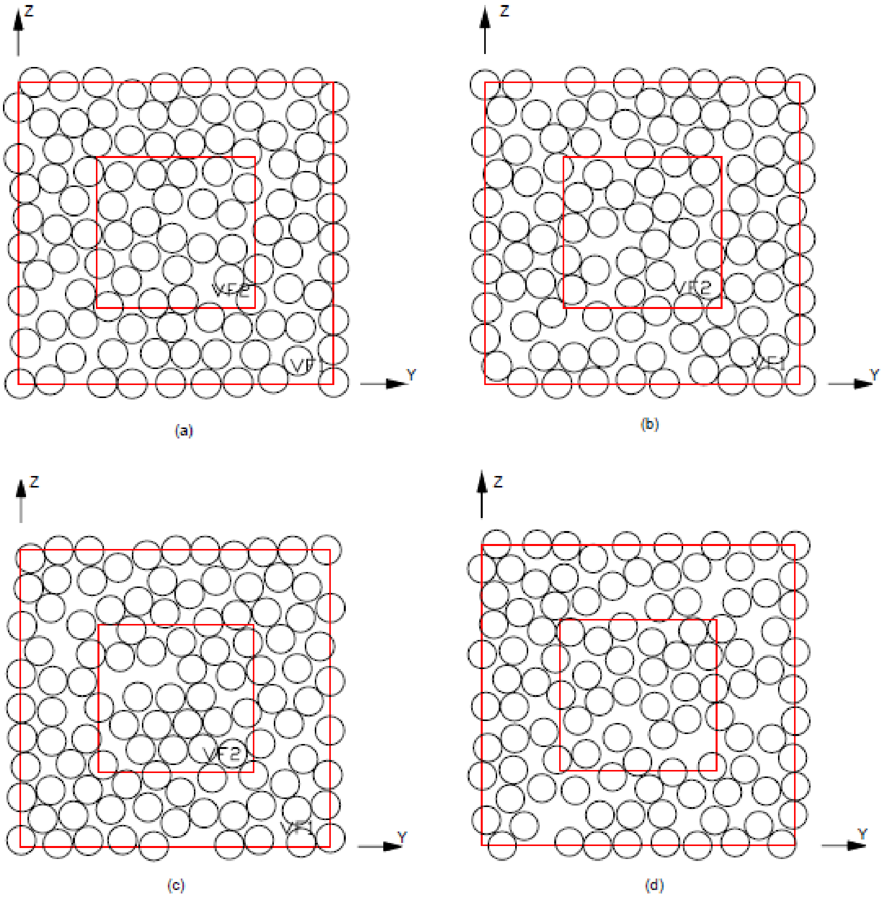


Fig. 8. Schematic diagram for perturbation process (Wongsto and Li, 2005) [41]



(a) (b) (c) (d)

Fig. 9. Random fibre distribution obtained after. (a) 265 iterations,(b) 286 iterations, (c) 382 iterations, (d) 262 iterations, (Wongsto and Li, 2005) [41]

Many researchers have reported that the stress concentration factors increase with increasing fibre volume fraction and the ratio of matrix and fibre material moduli. Researchers indicated that the monitored fracture mechanisms were different in specimens with low and high fibre contents. Fig. 10 shows the crack direction under transverse tension for silicon carbon/glass ceramic composite (Daniel et al. 1995) [12]. It can be seen from the figure that for closely packed fibres, radial cracks initiate at approximately 45° from the loading axis and 90° when fibres are farther apart. As the loading increases, interface cracks are formed in an area along the loading axis over an arc 20° from 0°.

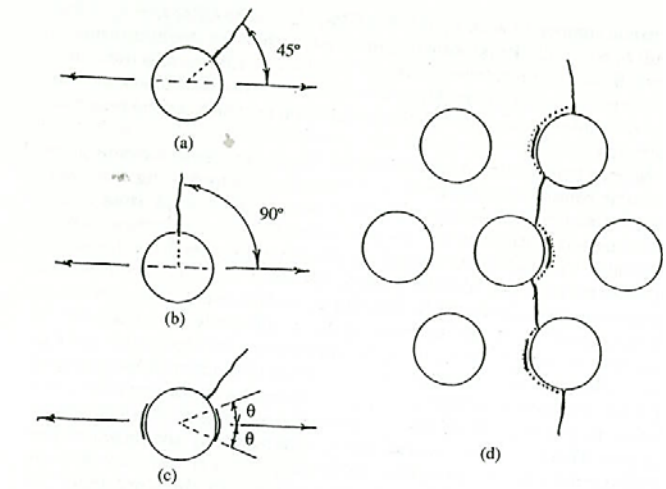


Fig. 10. Failure mechanisms and stages of damage development in a transversely loaded ceramic composite. (a) Initial radial cracks around closely packed fibres; (b) Initial radial cracks when fibres are farther apart; (c) Interfacial cracks; (d) Interconnection of radial and interfacial cracks (Daniel et al. 1995) [15].

Baral et al [42] indicated that the nature of the fibres has a strong influence on both interlaminar fracture energy and transverse tensile properties. Carbon fibres can be broken or tangled during production. This leads to damaged fibres, interface debonding and voids formation in the matrix which reduces the composite strength significantly. Blassiau et al [24] gave a detailed analysis of load distributions around fibre breaks in a composite and the mechanisms involved in load transfer. The model considers the elastic case with and without debonding at the broken fibre/matrix interface. In contrast to other studies, this analysis considers different configurations of composite damage from the failure of a few fibres to the failure of many.

Fibre to fibre distance is also an important factor affecting the composite performance under transverse loading. It has influence on matrix shrinkage as Vu, et al. (2012) [43] concluded that matrix shrinkage increases with conditioning time, fibre-to-fibre distance and oxygen pressure. In general, a composite microstructure with low local fibre-volume fraction (‘‘matrix-rich’’ zones) tend to exhibit numerous debonding sites, at the fibre/matrix interface. This certainly has a negative effect on composite fatigue life. Debonding in the interface between fibre and matrix due to matrix shrinkage after curing is shown in Fig. 11.

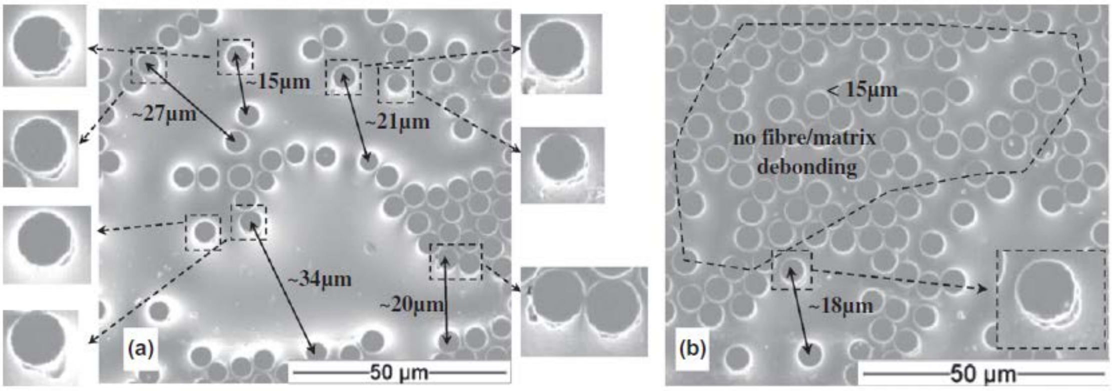


Fig. 11, Matrix shrinkage depth is affected by fibre to fibre distance in SEM under atmosphereic air at 150°C (Vu, et al. 2012) [43]

Dai at al. (2011) [44] also presented modelling, simulation and experimental characterisation of local shrinkage strains and stresses induced by thermo-oxidation phenomena in a composite material at high temperatures. It showed that higher fibre-to-fibre spacing has a negative effect on matrix shrinkage and hence composite fracture and failure. The shrinkage depth and average Von Mises stress increases with increasing fibre-to-fibre distance. It also concluded that the environment, the thermo-oxidation induced shrinkage and the viscoelastic behaviour of the polymer matrix play a critical role in the formation and development of the stress field.

2.2 The interface between fibre and matrix

In UD-FRP composites, interface plays an important role in the transverse strength. So far, the factors which affect the transverse strength include:

- Fibre preparation such as fibre quality, fibre surface treatment and sizing quality before production.
- Production conditions such as winding speed, temperature and humidity etc. which has influence on residual stress, resin viscosity etc.

Usually, before the fibre is ready for production, sizing will be applied. A sizing is a mixture of various chemicals, applied to the individual fibre to coat (‘size’) the fibres to improve the bonding to the matrix as shown in Fig. 12 (McMican, 2012)[45]. Different fibres may use different chemicals for sizing based on manufacturer’s knowhow techniques. A sizing layer on the surface usually uses solution or emulsion consisting of polymeric components. The sizing can alter the handle ability of carbon fibre which includes fibre protection, fibre alignment and fibre wettability (Dai et al. 2011) [44]. Material suppliers develop their own sizing technique and apply it to the fibre to best suit the needs of the targeted application [45[45]]. Dai et al. (2011) [44] reported that the sized fibres possess an improved wear resistant and 97% improvement of interfacial shear strength by comparing the unsized fibres. Thus, sizing stability and quality are key factor to the rotor quality. But Dai et al. (2011) [44] also indicated that not all kinds of sizing could improve interfacial adhesion between fibres and matrix. The interfacial shear strength (IFSS) for carbon fibre reinforced epoxy resin depends not only on the chemical bonding but also on the physical and adhesive interactions.

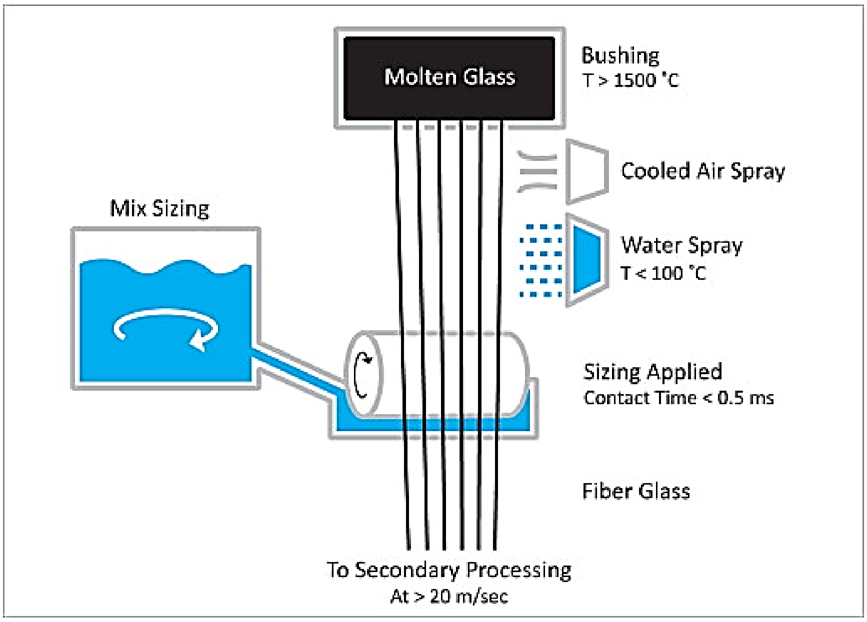


Fig. 12, Schematic graph showing sizing application in glass fibre manufacture (McMican, 2012) [45]

The interfacial bond strength between fibre and matrix (e.g., the composite shear strength) is often evaluated by measuring interfacial strength which is tested using different experiment methods. Among them, transverse tensile tests on composites were performed on at least five parallel sided specimens of width 25 mm of each material following ISO 527 by Baral et al [42]. In this test, elongation was measured using an extensometer and the loading rate was 1 mm/min. Strain-controlled tests are proposed by Shang [46] as only in that case the softening effects are included. While, the difficulty to carry out tests in this condition is that strain controlled tests needs test rig of very high frame stiffness.

Alternative approach to evaluate the interfacial strength is again to apply elastic mechanics or to establish finite element micromechanics model to understand the influencing factors which affect the bonding strength. In these analyses, two types of models are applied, one type of model has two phases: matrix and fibre; another type has three phases: matrix, fibre and interface between matrix and fibre. A three-phased micromechanics model is the more applicable to explain the stress transfer in fibre-reinforced composites under transverse loading. The analytical results generated from the models are usually compared with experimental data to validate the models.

In early studies, Folias et al. [47] investigated the 3D stress field of a cylindrical fibre embedded into a resin matrix to predict debonding initiation at the fibre– matrix interface by applying two phases model - fibre and matrix under a uniform tensile load. The strain energy release rate was computed and the criterion was used to predict debonding initiation at the fibre matrix interface. This paper indicated that failure was most likely to occur at the free surface, i.e. the region where the fibre intersected with holes, cut outs, edges, cracks, etc. are potential trouble spots. Moreover, the strain energy release rate may be used to predict crack initiation in the centre of the fibre length, as well as at the free surface. King et al. [48] presented a three phase finite element micromechanics model to estimate the influence of the matrix and interfacial bond strength on the composite shear strength for a given fibre–matrix composite. Numerical results generated from this model were compared with experimental data in order to validate the approach. A relative indication of the strength of the interfacial bond was then obtained by comparing the measured and the predicted composite shear strengths. This approach offered the ability to predict the maximum composite shear strength of a given fibre/matrix system, and to determine the effects of surface treatment and sizing on the shear strength. This paper also indicated that the fibre/matrix bond factor is independent of the type of matrix material (for the two relatively brittle matrix materials considered). And, it was predicted that the fibre volume variations in the 50 to 65 percent fibre volume range has little effect on the interfacial strength.

Later on, finite element micromechanics model has been applied by many researchers to investigate the interface effect (stiffness, strength, and toughness) on the transverse property. The interface is usually modelled with cohesive behaviour of traction–separation law which relates the separation displacement between the top and bottom faces of the element to the traction vector acting upon it in both two phases and three phase micromechanical finite element method (FEM) models[49, 50, 51,52, 53, 54, 55, 56]as shown in Fig. 13. In two phase model, the cohesive behaviour of traction–separation law for the contact elements between fibres and matrix is set while in three phase model, cohesive zone elements are applied. In the present analysis, an inhomogeneous interphase model by Anifantis [57] that assumes that the interphase has elastic properties which are changing with a radial distance from a fibre boundary was adopted. Over recent years interface elements have become increasingly used for modelling the progressive interface debonding, e.g. [58, 59, 60].

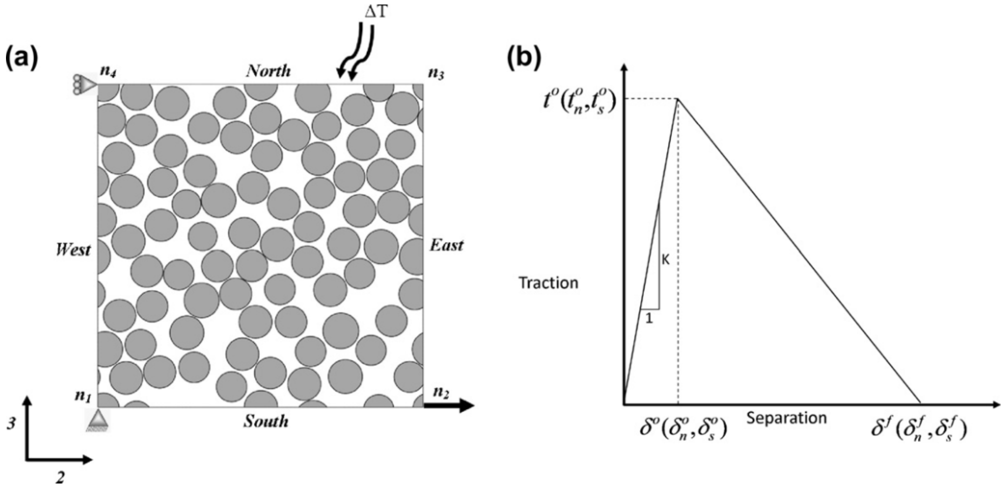


Fig. 13, (a) Periodic boundary conditions applied to RVE to simulate transverse tension. (b) Traction–separation law governing behaviour of cohesive elements (Vanghan, 2012) [55]

Among them, Alfano and Crisfield [59] proposed bilinear cohesive zone model (CZM) in order to characterize the constitutive behaviour of an interface, which introduces a normal and tangential displacement discontinuity on an interface. This model assumes softening relationships between tractions acting on the interface and corresponding relative displacements with an area under a traction–displacement curve being equated to the critical fracture energy.

Romanowicz, M. [53] developed a micromechanics model of fibre-reinforced composite subjected to transverse tension applying the unit cell approach and the finite element method to simulate the evolution of damage and to explain the softening mechanism. The model is shown in Fig. 14. The effect of complex features of imperfect bond between reinforcement and resin as well as randomly distributed fibres have been incorporated in the analysis. This paper indicated that the debonding growth at both a global and a local level has revealed that high stress concentrations in the neighborhood of the interface crack tips can lead to the ultimate failure of composite in the direction perpendicular to the loading direction after growing these microcracks to a critical length. It was also found that the post initial failure behaviour of unidirectional lamina under transverse tension is mainly controlled by the interface strength and the interphase stiffness. Also, the results have indicated that local fibre array irregularities are a significant contributor to matrix cracking through local stress concentrations and the occurrence of localization.

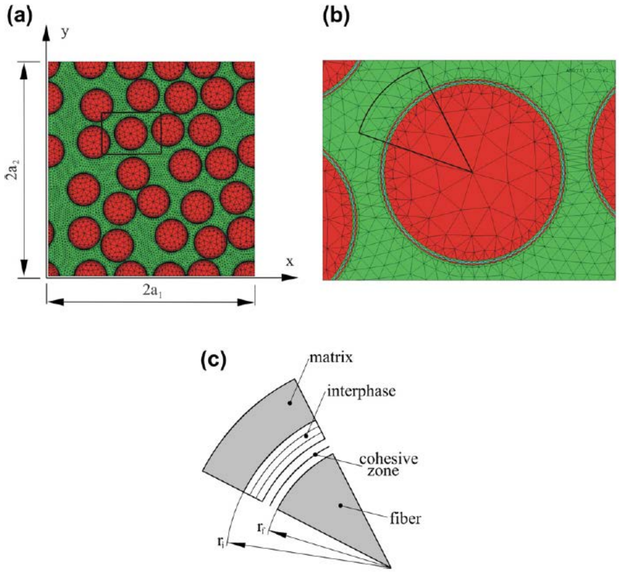


Fig. 14, Finite element of the RVE with fibres distributed at random for the fibre volume fraction V_f=49.56% (a) Whole periodic RVE for calculations. (b) One fibre for consideration in local analysis (c) Individual constituents. (Romanowicz, M. 2009) [53]

Romanowicz, M. [60] then developed the interface model by using both interface elements with vanishing thickness and interphase elements with specified thickness as he proposed that not only the progressive decohesion of the fibre/matrix interface but also the existence of an interphase with specified thickness have to be taken into account to the model.

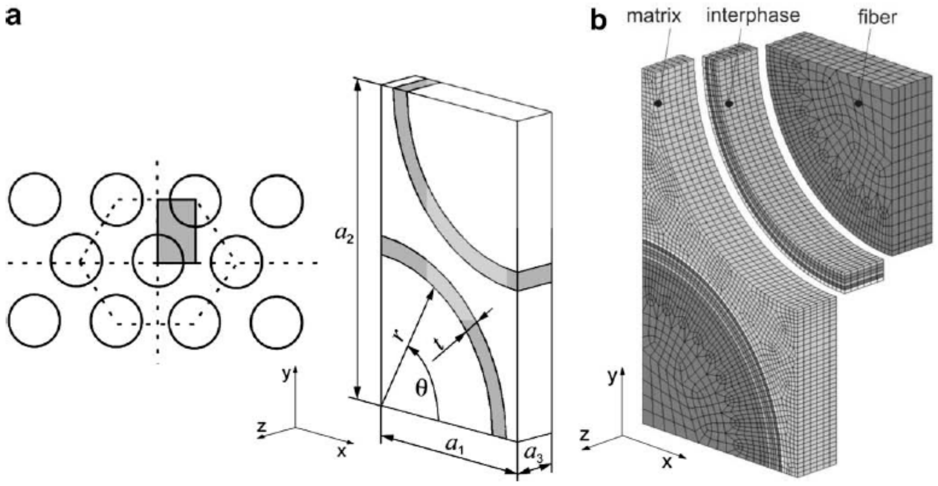


Fig. 15. Micromechanics model. (a) One-eighth model of the RVE (b) finite element discretion of the RVE (Romanowicz, M. 2009) [60]

Shang (2015) [46]indicated that the interface strength of each fibre in resin matrix composites has been proved to follow the Weibull distribution and composite transverse strength is also related to the stochastic fibre/ matrix interface strength. However, numerical models usually consider the interfaces with uniform mechanical parameters for simplicity. Therefore, Shang investigated the effect of Weibull distribution-based stochastic fibre/matrix interface strength on the transverse tensile strength and failure process of long fibre reinforced composites in represent volume elements. He concluded that failure path goes along interfaces of lower strength but not always the lowest strength and variation of fibre location distribution will lead to a different failure process. Influence of the two Weibull parameters (Weibull scale parameter and shape parameter k) on the transverse tensile strength was also investigated. The transverse tensile strength improves with the increase of Weibull scale parameter and shape parameter. A small value of shape parameter will lead to a scattered interface strength distribution and much lower transverse tensile strength.

Three phased Representative Volume Elements (RVEs) microscopic structure models were constructed to investigate the microscopic failure mechanisms by Yang (2015) [40]. The results show that the transverse shear failure of the composite is dominated by matrix plastic damage for higher interfacial strength, while the in-plane shear failure of the composite is initiated by interfacial debonding and then dominated by matrix damage. It is also found that the fibre distribution has obvious influence on the damage initiation position and propagation path of the composites under shear loading.

Furthermore, the stress concentration is not only due to the structure of composites which is a mixture of matrix and fibres, but also due to the mismatch of material moduli and thermal expansion coefficients of matrix and fibres. And other factors such as residual curing stresses can also affect failure of unidirectional fibre composites under transverse tension. All these factors must be accounted for appropriately. Fig. 16 shows SEM observations of transverse tensile failure for unidirectional M55J/epoxy composite and pitch fibre reinforced composite from Baral et al. (2006)[42]. It can be seen that the crack in Fig. 16(a) is along the interface of matrix and fibre while in Fig. 16(b) the crack passes through the fibre. This is due to different mechanical properties of matrix and fibre pair and their interfacial properties.

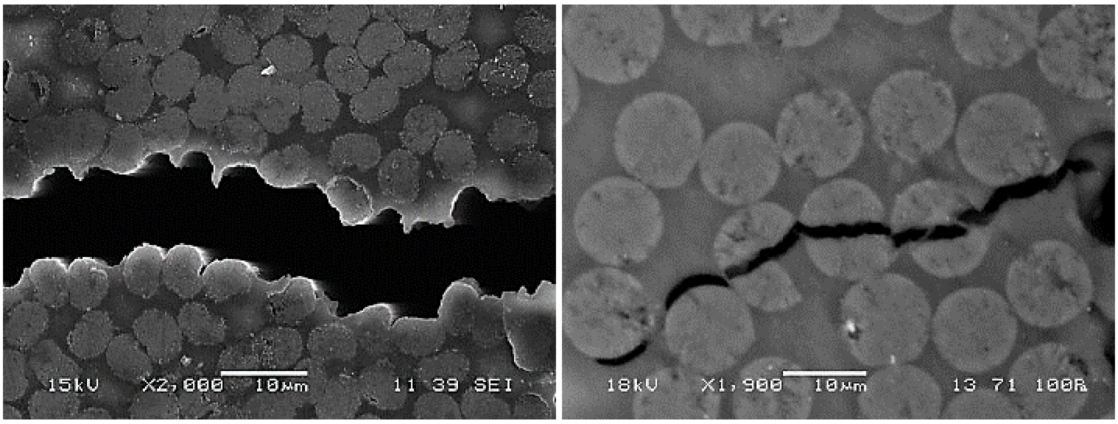


Fig. 16, SEM observation of transverse tensile failure (a) Unidirectional M55J/epoxy composite and (b) pitch fibre reinforced composite (Baral et al. 2006[42])

Vaughan [55] carried out micromechanics damage model to investigate the transverse fracture behaviour of a carbon fibre/epoxy composite under thermal residual stress and cyclic loading. The behaviour of the fibre–matrix interface was modelled using cohesive elements. The presence of thermal residual stress was found to alter the microscopic stress state significantly. It is effective in offsetting interfacial decohesion as a result of thermally induced compressive stresses acting at the fibre–matrix interface. It was also found that for a weak fibre–matrix interface, the presence of thermal residual stress can induce damage prior to mechanical loading. However, for a strong fibre–matrix interface the presence of thermal residual stress is effective in suppressing fibre–matrix debonding and improving overall transverse strength by approximately 7%.

2.3 The matrix

In micromechanics analysis for UD FRC material, plasticity model for matrix is always applied. The plasticity model is able to characterize the plastic response of different kinds of composite materials. The mechanisms of damage accumulation in fibre–reinforced composites can be time dependent due to the viscoelastic properties of the matrix. The relaxation of the viscoelastic matrix around the damaged fibres results in a changing state of stress around the neighbouring fibres. The plasticity model Xie et al [61] developed has been implemented in a three-dimensional elastic-plastic finite element analysis to study compression and short-beam shear test configurations. Blassiau [24] carried out a local three-dimensional (3D) finite element analysis (FEA) to investigate the mechanisms of composite damage in the region around a fibre break. The model considers viscoelastic and plastic matrix behaviours with and without debonding at the broken fibre/matrix interface. The plastic behaviour of the matrix has been shown to have consequences on reloading after unloading.

Voids and porosity in matrix are critical imperfections in fibre reinforced composite materials and have a detrimental effect on the matrix dominated compressive, interlaminar shear and flexural properties and voids are unavoidable in the process of production [62-636465666768697071727374]. Voids and porosity has adverse effect on UD FRC due to a number of factors including free surface caused by voids in fibre-matrix adhesion, reduction of the cross-sectional area which leads to failure initiator and crack propagation.

Voids are formed due to a number of reasons, which include inability to remove gases trapped in the initial manufacturing stages in cure reaction, moisture absorbed during the material storing and processing[62,73], the use of a high-viscosity resin combined with closely packed fibers that are not completely wetted by resin, inadequate values of temperature and pressure or inadequate vacuum process[64-74]. Voids are not only formed from initial production, but also influenced by mechanical properties of fiber, matrix and interface; mechanical loads present and their nature (static or cyclic), environmental factors such as service temperature and moisture absorption etc. to magnify its effect [67,72,75]

Traditionally, voids are measured and quantified using optical microscopic techniques. But the disadvantage of this technique is that it can only provide a small observation area and the parts need to be chopped into small specimens and the initiation and propagation of damage from voids cannot be monitored in-situ. Recently, non-destructively X-ray tomography has been used to study the internal structure of composites [75,76]. Non-destructive technique also includes ultrasonic inspection, either by pulse echo or by transmission, has found widespread use in detecting the voids. This technique is able to detect defects that cause ultrasonic attenuation such as voids, delaminations, interlaminar cracks, inclusions, foreign object damage, degree of cure of the laminate, resin rich or resin starved areas, fiber misalignment, and degradation due to environmental conditions[71]. The voids in fibre reinforced composites as shown in Fig. 17 has size of tens of micros which are smaller than 0.1mm, therefore many voids are unable to be detected by CT or ultrasound, but could be very critical to composite fracture and failure.

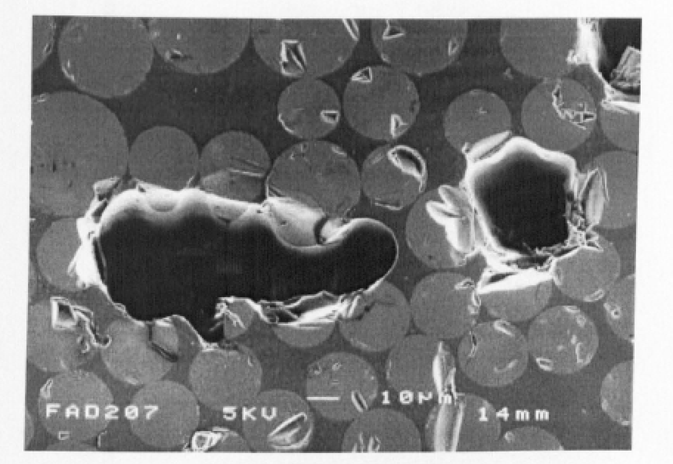


Fig. 17, CFRC under SEM (Emerson, 1997) [77]

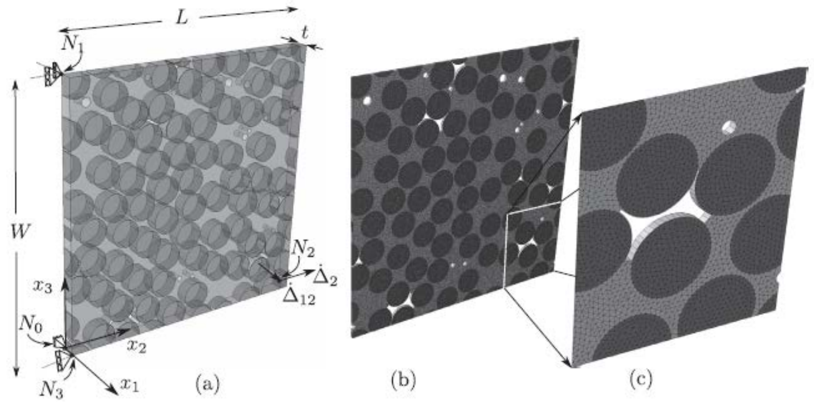
The effect of voids on mechanical behaviour of a composite with under different types of mechanical loading has been widely studied. All researchers agree that as the void content reduces the effect on mechanical properties decreases [73,78,79,80] and that there may be a critical void content below which there is no improvement in the mechanical properties [78, 79,84]. Most works consider the interlaminar shear strength [67-69, 81,82,83,84,85,86], however, there is no general agreement over the magnitude of the effect of porosity on the mechanical properties of composites and the value of critical void content. Chamber (2006) [80] indicated that: “For loads up to 80% of the failure load, the only damage observed was fine matrix cracking. The origin of these cracks was not associated with voids. At loads greater than 80% of the failure loads, broad cracks started to open up in the resin rich regions which predominantly lay between the plies and perpendicular to the loading direction”. This means that the voids played a major role in this process as the large voids were located in the resin rich regions. The research supports the concept of a ‘critical defect’ which takes account of size, shape, distribution and the composite fracture toughness.” [80] In another paper Suhot, et al. (2014) [87] which Chamber was a co-author found that a 2% increase in void content reduced the flexural strength by 12.7% for carbon/epoxy composites. Jeong [62] suggested that a critical void content is 1% applying a fracture mechanics approach to investigate the effect of void content.

Costa et al. [52, 68,69] reported the influence of environmental conditions on the strength of laminates with voids is extremely complex and involves a large number of variables including temperature and humidity. The failure criterion fits the experimental data reasonably well. The application of the fracture criterion suggested by Almeida [81] fits the experimental data well. And they all agree that there is a critical void content below which the strength of the laminate is not significantly affected by the presence of the voids.

The effect of void shape, size and distribution was investigated by Wisnon, Reynolds and Gwilliam [88] applying discrete and distributed voids in UD FRP. The results show that the interlaminar shear strength (ILSS) decreases by 20% as the void aspect ratio increases from 1–4. They also indicated that it is necessary to characterise the voids in order to understand the effect of voids on the flexural fatigue life and mechanisms. Lundstrom [89] investigated the effect of voids on their origin and location. He described two types of voids: cylindrical voids within the bundles and spherical voids between the bundles. It was found that cylindrical voids are more likely to be trapped than spherical voids. Bowles and Frimpong [63] observed that the distribution of voids in low void material was less homogenous.

Although void sizes, shapes and distribution all need to be take into account for composite fracture toughness, it is not a simple task. The difficulty encountered lie in two aspects: characterisation of voids size, shape and distribution which involves large number of describing parameters. It also involves the difficulties of measuring them accurately as the voids information for a particular part from the void measurement captures average value over a given volume rather than the information on the shape, size, and distribution of the voids. Also methods based on weight and density and non-destructive techniques such as ultrasonics are inaccurate at void levels <1%, whereas image analysis is both destructive and time consuming [80].

The improved knowledge on how voids influence the failure mechanisms including fiber failure, matrix cracking, fiber/matrix interfacial debonding, numerical models can be applied with matrix porosity. Vajari et al. [50,90] carried out several numerical studies on the effect of microvoids on the mechanical response of composites. The model includes randomly distribution of fibers and microvoids embedded in the matrix. Two different populations of voids were explicitly represented in the microstructure: Inter-fiber voids and circular voids within the matrix. The matrix followed the modified Drucker–Prager yield surface which includes the inherent pressure-dependency of the epoxy resins. The results showed that increase of the void volume fraction and decrease of the fiber/matrix interfacial toughness can significantly reduce the macroscopic ultimate strength of composites. It was also found that damage often initiates around the inter-fiber trapped voids while the role of the cylindrical microvoids appears when the matrix deformation is the dominant failure mechanism in comparison with interfacial debonding. In general, stress concentration around the larger voids leads to trigger the onset of damage in lower load-carrying capacities. Deformation of larger microvoids is decisive for crack initiations while the smaller microvoids may influence the path of crack propagation. Vajari et al. [90] found that even 1 % void volume fraction can significantly reduce the macroscopic mechanical response of composites.



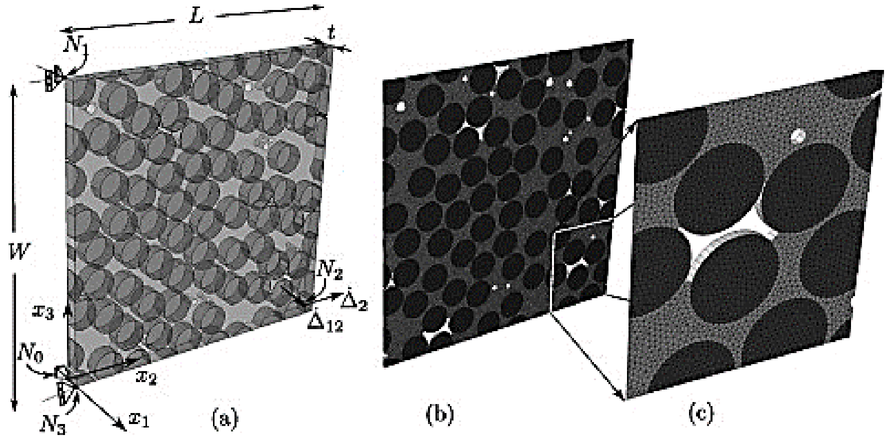


Fig. 18, (a) Illustration of the fiber and void distribution in a cross-section of a fiber-reinforced composite. (b) Finite element mesh of the cell. (c) A close view of the mesh near a trapped void is shown. (Vajari et al, 2014) [53]

3 Conclusions

FRP composites have attractive mechanical and physical properties that are now extendedly utilized in aerospace, automotive, construction, marine and other technical applications over the decades world-wide. But the strength under transverse tension is much smaller than that of under longitudinal tension mainly due to the lack of fibre strength in the transverse direction. This paper reviewed the research works on understanding the effects of the microstructure of a composite material (including fibre volume, fibre distribution, bonding quality between fibres and matrix, and characteristics of matrix) on the performance of FRP composites, and the mechanisms of their fracture and failure under different loads especially under transverse loading. Fibre characteristics including fibre nature, fibre diameters, fibre volume fraction, fibre distribution, fibre array and fibre spacing all have influence in transverse tensile strength. In UD-FRP composites, interface plays an important role in the transverse strength. The interfacial bond strength between fibre and matrix (e.g., the composite shear strength) is often evaluated by measuring interfacial strength by experiment methods or by applying elastic mechanics or to establish finite element micromechanics model to understand the influencing factors which affect the bonding strength. Voids and porosity in matrix are critical imperfections in fibre reinforced composite materials and have a detrimental effect on the matrix properties. The void sizes, shapes and distribution all need to be taken into account for a full picture of the effect of matrix on the performance of composite materials.

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