

Micro-mechanical Response of Continuous and Discontinuous Fiber Composites with Support of Computational Software

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Abstract

The paper presents basic principles of stress distribution in composite materials reinforced by fibers using the hFEM and pFEM numerical models of squared unit cell (UC). Moreover, paper provides the basic approaches to numerical modeling of composite materials reinforced by short (discontinuous) and continuous fibers and depicts a common and distinctive features of their mechanical behaviour through the analysis of micro-mechanical response.

Keywords: Matrix-Fiber, Micro-mechanics, Stress, Fiber length, Laminate.

1. Introduction

The real material structures consist of different types of in-homogeneities. These in-homogeneities are stress concentrators and cause various local effects. The material micro-structure implies holes, cavities, cracks, inclusions and the material micro-structure can also imply particles and short fibres (straight, curved, waved, continuous fibres). The last mentioned structures are called reinforcing elements as they cause improving the properties. The useful combination of reinforcing elements (shape, size, volume fraction of reinforcing elements, arrangement etc.) and matrix can form the new material – composite material with needful properties.

There are two types of fibre composites: reinforced by continuous (long) and discontinuous (short) fibres. The criteria of classification are different. According to [1] the fiber length of short-fiber composites is significantly smaller compared to the size of the component. The length of continuous (long) fibers is comparable to the size of the component. Another criteria indicator according to literature [2] is aspect ratio, i.e. the ratio of the fiber length L to the diameter D . If aspect ratio L/D is less than 100 ($L/D < 100$) then it is short-fiber composite. If the $L/D > 100$ then the fibers are considered to be long fibers. The long fibers are called also continuous fibers if their length is equal to the size of the component.

The criteria of classification are very coarse and needs to be clarified and completed. In this paper, the short fibers are considered fibers even of $L/D > 100$ because their dimensions are much smaller than the size of the

component. Such fibers are named relatively short fibers. For example, the diameter of nanotubes can be 4 nm and length even more than 1 mm, i.e. length to diameter ratio L/D is more than 250 000.

The short and relatively short fibres are oriented either randomly or preferably with unidirectional orientation. Such fibres are typical for components made by extrusion, injection moulding or made of non-woven fabrics.

We use computer simulation by commercial computational software to investigate the relations in material structure. P-version and h-version of classical FEM are used in the analyses of microscopic fields. The aim of analyses is micro-mechanical response, especially:

- the distribution of stress,
- the changes due to variable volume fraction of particles and fibers,
- the changes due to other parameters,
- the changes in von Mises Stress and Shear Stress due to size of particles and fibers,
- the comparisons with homogenous material.

2. Micro-mechanical analyses

Micromechanics-based simulations of heterogeneous materials play a major role in the development of new material systems. [3] At the very fundamental level, micromechanical analysis facilitates understanding of how the local properties of constituent phases and their arrangement influence the macroscopic material and structural behavior. [3] The estimation of macroscopic material properties of composite materials is a serious scope of research. The homogenisation (analytical, numerical) is approach of estimation the macroscopic properties according to the micro-structural parameters (micro-mechanics). The homogenisation is mechanics modelling scheme that transforms heterogeneous material into equivalent body of homogeneous continuum thus effective or homogenized material properties are used instead of taking into account the individual component properties and geometrical arrangements. These effective properties are usually difficult or expensive to measure and in the design stage the composition may vary substantially.

Homogenisation is the essential first step towards the design and analysis of larger scale and loaded structures. Many engineering problems are solved at macroscopic scale with such homogenized properties. However, sometimes such analyses are not accurate enough. There are many homogenisation theories and methods. [3, 4, 5, 6] The concept of representative volume element (RVE) and/or unit cell (UC) is used. The most composite materials exhibit statistical homogeneity. [7] Hill, R. [8] defines a representative volume element (RVE), which is entirely typical of the whole mixture on average and contains a sufficient number of inclusions for the apparent overall properties to be effectively independent of the boundary conditions. RVE as any block of material the analyst wants to use for the micromechanical analysis to find the effective properties and replace it with an equivalent homogeneous material. [9, 10] The term unit cell (UC) is also used extensively in the literature and defined as the building block of the heterogeneous material. We define UC as the smallest RVE. In other words, one RVE could contain several UCs. RVE represents the repetitive unit cell – periodic micro-structure. In case of randomly distributed reinforcing elements of different dimensions and geometry, the concept of statistical representation of representative volume element (RVE) and repeating unit cell (RUC) is used. [3, 11]

2.1 Discontinuous fibers

The short-fiber composite materials are made for example of carbon, ceramic, metal, polymers, glass, etc. with matrixes of polymers, metals and ceramics.

The square pattern is a reason for use of square UCs. As the advantage of UC symmetry of geometry and boundary conditions is used, the eights of models are modelled and computed (Fig. 1, right). The constant displacement in the direction of y-axis equals to 5×10^{-5} . It is prescribed in the whole upper surface. The dimensionless model is used. The symmetry boundary conditions are defined for the other 5 surfaces. The following assumptions of computing are:

- The fibers are straight, cylindrical. The particles and fibers are regularly distributed without overlapped configuration.
- The ends of each fiber are modelled as half-spheres to avoid singularity.
- The particle (fiber) and matrix create the continuous material without gaps and slip.
- The material of both matrix and particle (fiber) is considered to be isotropic linear elastic.
- Any interface layer is not assumed between fiber and matrix.

- The ideal cohesion between matrix and particle (fiber) is assumed.

The numerical analyses showed that the most stressed locations are the middle part of fiber, interface fiber/matrix, ends of fibers in case of no-overlapping fibers. In case of overlapping fibers the larger stress is also in such parts of fibers that are close to end of neighboring fiber. The stress concentration on the fiber end influencing the stress distribution in the neighboring fiber. The most stressed locations are responsible for de-cohesion and re-cohesion, de-bonding of fibres, fracture of fibre.

The use of composite material does not mean the lower stress in micro-structure, but means much higher modulus of elasticity of structure and carrying capacity. Comparing stress values in matrix and fiber, the larger stress is in fibers. Naturally, the ultimate stress of fiber material is much higher than that of matrix. The fibers are load carrying phase of composite.

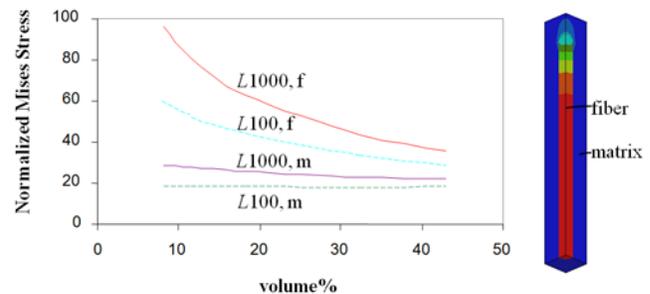


Fig. 1 Normalized von Mises Stress in matrix and fibers R1 (f – fiber, m–matrix), (left), Mises Stress distribution in UC (right).

Fig. 1, left, shows the typical attribute of fiber composites: the lower volume fraction of fiber the larger stress in fiber. Normalized stress means ratio σ_{VM}/σ_0 where σ_{VM} is maximum von Mises stress and σ_0 is maximum von Mises stress in material without reinforcing element, i.e. only “pore”. For compared cases in the figure, the von Mises stress is 2.2 – 3.3 times larger in fiber (in dependence on aspect ratio of modulus of elasticity) when volume fraction is the lowest (9 vol%). The stress in the fibre can exceed the largest stresses in the matrix by several orders. Fig. 1, right, provides the stress distribution in UC.

If we analyze the same for spherical particulate composite, the graph would have the opposite slope. It means the larger volume fraction of particulate reinforcing element, the larger normalized Mises stress. Therefore, the spherical particulate composites are designed to produce unusual combination of properties rather than to improve strength.

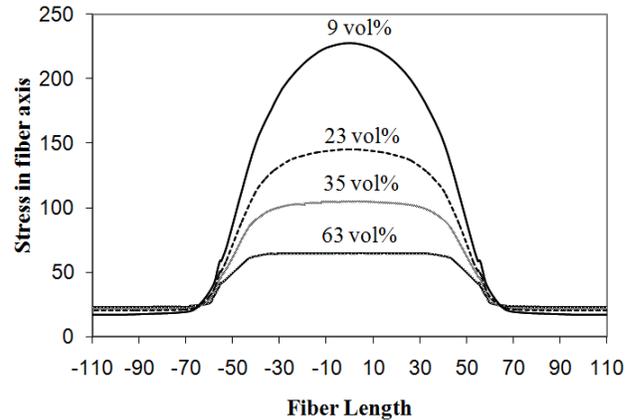
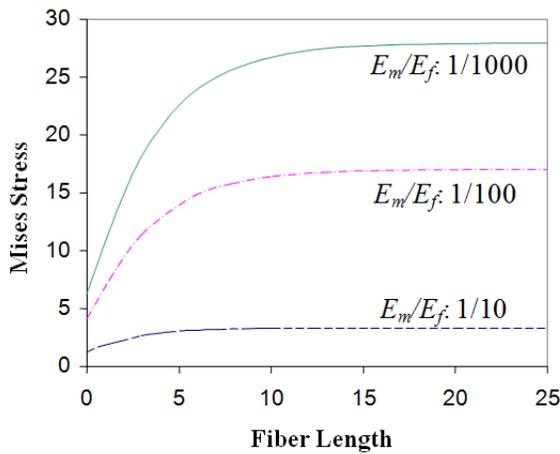


Fig. 3 Mises stress in fiber axis due to change of fiber volume fraction

Fig. 3 provides the influence of another parameter, i.e. volume fraction. The more fibers in volume, the lower stress in each fiber. If the volume fraction is 7-times larger, the Mises stress is only 3.75 lower.

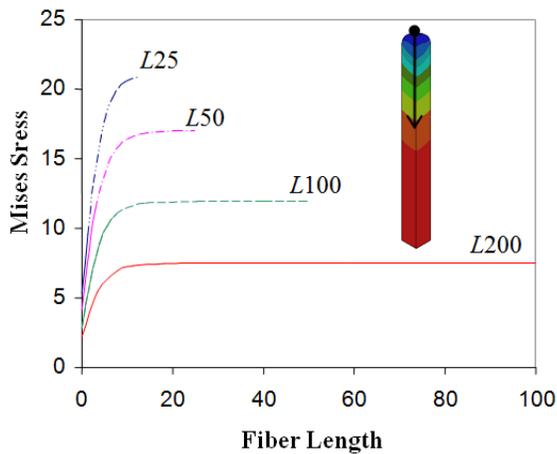


Fig. 2 Mises Stress of fiber L50/R1 for various E_m/E_f (up) and Mises Stress due to fiber length, $E_m/E_f : 1/100$ (down)

Fig. 2, up, presents the sensitivity of short fiber composite to matrix and fiber material properties, namely E_m and E_f is Young modulus of matrix and fiber, respectively. Naturally, the larger difference in fiber and matrix material properties, the larger stress in fiber. But if the ratio E_m/E_f (compare 1:10 and 1:1000) is larger 100-times, the Mises stress is larger only about 10-times keeping the same dimensions and boundary conditions. The stiffer fiber in matrix is not disadvantage.

Fig. 2, down, shows the relationship between fiber length and Mises Stress. The material properties and boundary condition are the same for each numerical model. The middle part of fibre carries the largest stress. If the fiber length is 8-times larger (compare L25 and L200), the Mises stress is 3-times lower.

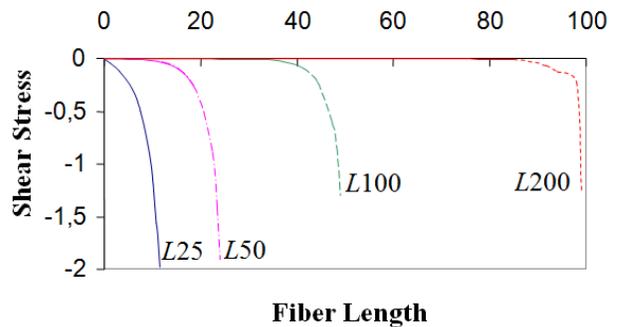
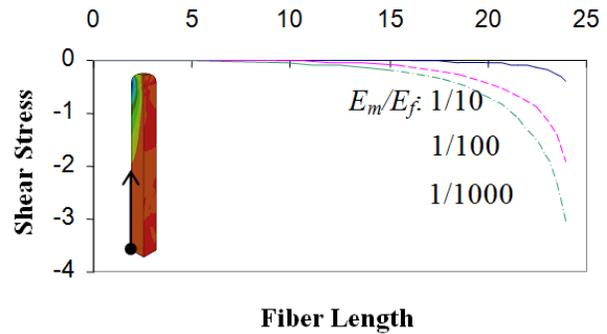


Fig. 4 Shear Stress in fiber/matrix interface of fiber of fiber L50/R1 for various E_m/E_f (up) and Shear Stress due to fiber length $E_m/E_f : 1/100$ (down)

Fig. 4 is analogous to Fig. 2, but it is applied to Shear Stress on the fiber-matrix interface. The fiber ends and fiber-matrix interface are important and critical locations of composite material regarding its strength and material properties. The largest Shear stress is in the fiber ends on fiber surface (Fig. 4). The fiber ends cause the maximum stress in matrix placed near fiber end. Matrix material has lower ultimate stress than fiber and the ends become the

areas of beginning of matrix damage. Maximum shear stress between the fibre and the matrix can result in de-bonding of the fibres or to de-cohesion and re-cohesion at the ends and also in the middle of a fibre close to neighboring fibre. The elasticity and strength limit of composite material depend on the connectivity between fiber and matrix, not only on suitable combination of matrix/fiber materials. However, the aim is not to make the stiff connection at the ends as it would seem as it causes the very high gradients of shear stress at the ends. Nevertheless, the effect of de-cohesion and re-cohesion at the ends of fibers are appropriate regarding material damping.

2.2 Continuous fibers

Laminate composites are well known composite materials applied in the aerospace industry and extend from commercial to military aircraft. According to [12] a lamina or ply is a typical sheet of composite material; a laminate is a collection of laminae (plies) stacked to achieve the desire stiffness and thickness. Moreover, the sequence of various orientations of a fibre-reinforced composite layer in a laminate is termed the lamination scheme (or stacking sequence).

The most of commercial software have involved the modules for numerical simulation of laminates based on plate theory. Classical theory originally developed for thin elastic shells are based on the Love-Kirchhoff assumptions (thin plate theory or Kirchhoff's classical plate theory); more in [13, 14, 15]. This theory neglects the effect of transverse shear deformations. Classical lamina theory is applicable to orthotropic continuous fibre laminated composites only. The Mindlin–Reissner plate theory (thick plate theory) is an extension of Kirchhoff–Love plate theory that takes into account shear deformations through-the-thickness of a plate. [12, 13]

The individual plies suitable for numerical simulations by use of plate theories are unidirectional and bidirectional. The woven and randomly distributed fibres in plies need the different approaches based conception of RVE or UC to estimate the material properties of such ply.

2.2.1 General approach to make the numerical laminate model

The following approach is general for commercial software. It can be different in details. The used figures are of Abaqus.

1. Modeling the CAD model

The numerical models of laminates are modeled as plates or shells (that have same characteristics as plates, but curvature is an additional one). Shells are sometimes referred to as curved plates

or a plate may be considered as a special limiting case of a shell that has no curvature. The thickness h is much smaller than the typical plate dimension L , $h \ll L$. The presented model is defined as 3D shell model meshed by 2D shell elements.

2. Defining material axes regarding the coordinate system

The laminates are directionally oriented materials. Material axes are denoted 1, 2, 3. Material axis 1 is axis of fiber direction.

3. Defining the ply material properties.

Material constants for presented model are Young modulus (E_1, E_2) in direction s 1, 2, Poisson's ratio (ν_{12}) and shear modulus (G_{12}, G_{13}, G_{23}) as shown in Tab. 1. The specific values can be define according to material lists (in presented model) that are estimated experimentally or numerically by concept of RVE or UC or analytically. Tab. 1 provides the material properties of core and glass-epoxy lamina.

Table 1: Material properties of core and lamina

Material	Core	Lamina
E1 [MPa]	10	35000
E2 [MPa]	10	7500
Nu12	0.3	0.3
G12 [MPa]	1	3600
G13 [MPa]	30	3000
G23 [MPa]	30	3000

4. Defining the laminate

The laminate is characterized by several parameters, as following: number of plies, ply thickness, layup orientation regarding global coordinate system and laminate (layup) sequence. The presented model involves core and symmetry layup where midplane is represented by core that is to receive the added layers.

5. Assigning the laminate to model.

6. Computing and interpreting results

Stress distribution in ply 8 is shown in Fig. 5.

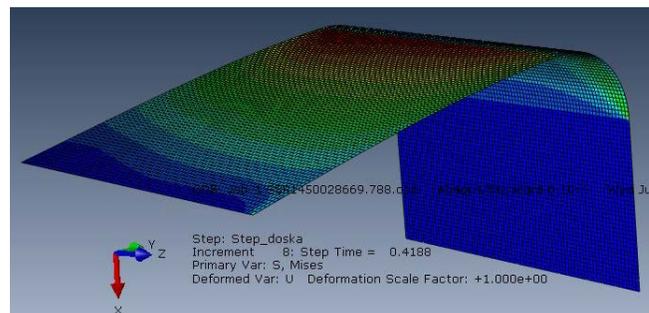


Fig. 5 Ply 8- stress distribution

Table 2: Comparison of two different laminate layup configurations

Ply	Composite layup 1		Composite layup 2		Thick-ness [mm]
	Max. Mises Stress [MPa]	Angle [°]	Max. Mises Stress [MPa]	Angle [°]	
1	643.9	-60	310.0	45	0.15
2	1390.0	-30	658.8	0	0.05
3	733.6	0	338.8	-45	0.05
4	1000.2	30	528.4	90	0.05
5	442.1	60	212.1	45	0.05
6	0.087	0	0.046	0	1
7	405.7	60	199.3	45	0.05
8	781.3	30	398.7	90	0.05
9	694.7	0	327.4	-45	0.05
10	1256.0	-30	599.0	0	0.05
11	607.5	-60	297.2	45	0.15

3 Conclusion

The paper presents basic principles of stress distribution in composite materials reinforced by fibers using the hFEM and pFEM numerical models of square UC. Moreover, paper the basic approaches to numerical modeling of composite materials reinforced by short (discontinuous) and continuous fibers.

It was confirmed that the final micro-mechanical response of short (discontinuous) and continuous placed in matrix is different; the reinforcing elements are load carrying elements; the connectivity of matrix and reinforcing elements and interface between matrix and reinforcing elements are very important. The composites reinforced by continuous fibers are easier for numerical simulation as the commercial software involve the modules intended for laminates or there are specialized software. In generally, the critical step of numerical simulation is material properties estimation.

The analyses show the fibers are used mainly for improving the composite material strength and the material properties of new (composite) material depend on several parameters (matrix/fiber, Young modulus ratio, fiber length, aspect ratio of fiber, volume fractions etc.) that need to be optimized. Moreover, the distribution of fibers and their interactions influences the macro-mechanical behaviour. It has to be taken into account when designing the composite material.

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