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Static and Dynamic Analysis of Polymer Composites Containing Void Defects

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Abstract

Polymer-matrix composites are utilized in several engineering applications, since they have high stiffness and specific strength. However, bubbles may be formed in the matrix due to gases or water entrapment during fiber reinforcement impregnation with resin or during laying process. Voids or air bubbles are generally undesirable because they diminish strength and create gaps in the polymeric matrix. The finite element method (FEM) was utilized in this research in order to study static and dynamic analysis of void-containing micropolar polymers. The Euler–Lagrangian formalism is utilized based on formulations of kinetic energy, potential energy, and mechanical work formulations. As a result, the static and dynamic responses of such system can be studied. The matrix coefficients for each scenario are determined by the shape functions used. The reported results are illustrated via an application.

1. Introduction

Polymeric materials have gotten a lot of attention in the industrial and scientific sectors. These materials serve as the foundation for a variety of engineering applications, including photolithography in micro-electro-mechanical systems (MEMS), as well as adhesive bonding in both civil infrastructures and aerospace industry. Polymeric materials are becoming increasingly popular because they offer cheaper devices and manufacture, and most importantly, their extraordinary physical qualities give them many advantages for their use in many products [1]. However, voids in these materials may form during the production process [2-4] or as a result of events that occur during their use [2]. Voids are matter's empty spaces. In most circumstances [3, 4], voids are undesirable in polymer-matrix composites because they can have a negative impact on mechanical characteristics [3-5] by changing the structure's stress field [5].

Void defects formation in polymer-matrix composites can be attributable to a variety of factors, including the formation of air bubbles during the manufacturing process as well as moisture that dissolves in the thermosetting resin during the manufacturing and storage processes. This suggests that voids are unavoidable in polymer-matrix composite systems [5]. The intrinsic gaps (voids) constitute free volume, and increasing free volume allows polymer molecules to move more freely [6]. The study of voids in composites began roughly a half-century ago and is currently an active research subject in the composites field. This is due to the persistent lack of knowledge and uncertainty about void as well as the challenges of suppressing them in modern production procedures such as processing outside of autoclaves and high complexity parts, which are made more difficult by the increased modified resins viscosity. In additions due to the rising interest in achieving more accurate limits of void rejection that would allow some void age to be maintained [7].

The detection and analysis of composites-contains void defects can made by using some techniques like visual inspection of cross-sections, density method, and ultrasonic C-scan [8]. Void content of the sample measured in the ASTM method [9] according to its mass per unit volume. Despite, voids have no mass and can be neglected; they participated in increasing the sample size. However, is difficult to determine the void-free density of the composite and is generally measured from the measured values of the fiber and resin density and the weight fraction of fiber. The matrix may be dissolved in acid or burned-off [10] in order to eliminate fibers from it and calculate its weight; however, acids maybe destroy the fibers and eliminate the mass, resulting in erroneous results. The accuracy of this method is questioned especially when small void contents are presented [3].

Despite the efforts of various researchers [11-16] to optimize the polymer manufacturing process, the formation of voids cannot be fully avoided. As a result, it's crucial to comprehend and predict how void defects will affect the properties of these composites.

The linear theory of elasticity is commonly used with steel, wood, coal, and concrete to study their mechanical behavior, but this theory cannot be used with polymers or elastomers to study or analyze their properties [17].

The properties of materials with voids were first studied by Goodman [18]. The main point made was that an additional kinematic freedom degree to be considered. According to this novel parameter, the theory created to characterize the flowing granular materials behavior.

Several papers have employed FEM to study the impact of void defects on the mechanical properties of fiber reinforced polymer (FRP) composites under the assumption of uniform void and fiber distribution.

When void content is between 1-3%, the transverse shear modulus of unidirectional fiber reinforced plastics (UD-FRPs) with void defects drops by as much as 15%, according to Tai and Kaw [13]. Hyde et al. [14] devised two-dimensional (2D) micromechanics FEM for predicting the mechanical characteristics of void-filled composites. In comparison to the in-plane tensile modulus, Mekonnen et al. [15] discovered that void defects produce a higher drop in the shear and tensile modulus of the out of plane. A two-scale integrated methodology for simulating the cracking of matrix in sections with voids has been suggested by Mehdikhani et al. [16]. Wang et al. [19] used an image-based FEM to investigate the effect of voids on the mechanical properties of plain weave carbon fiber reinforced polymer (CFRP) composites and discovered that void flaws have a substantial effect on the Young's modulus. The influence of void content on the thermoplastic composites' flexural fracture behavior investigated by Hayashi et al. [20], they discovered that as porosity increased, the flexural strength decreased dramatically. In these representative volume elements (RVE)-based FEMs, however, the voids and fibers are considered to be mostly distributed in the 2D plane, and they neglected the longitudinal direction. Furthermore, these models are unable to use for the purpose of engineering constants prediction in the longitudinal direction. To examine the impact of void distribution on the UD-FRPs' stiffness properties, three dimensional (3D) RVE models with randomly sizes and contents voids and fiber are required. Based on some test results, Dong [21] suggested a mathematical fitting model to easily anticipate the stiffness parameters of unidirectional FRPs.

Shen [22], Summer scales [23], and Wu [24] studied the behavior of polymers with voids using theoretical models in order to determine their physical properties. The FEM was employed less to polymers with void, due to the intricacy of the required processes [25]. Experimental methods have been used in more studies to investigate the voids polymers properties. Various elastic constants required for the systems design based on polymeric materials can be determined in this way [25-29].

The FEM has recently undergone significant development, allowing it to analyze mechanical structures of various materials, such as sandwich types, composites, anisotropic, isotropic, transversely isotropic, or under special conditions, such as the temperature field [30-32].

For the analysis of mechanical systems, a variety of computation approaches are used, all of which produce essentially comparable findings. Generally, analytical mechanics is the finest analysis tool for complex systems. Analytical approaches continue to be the greatest alternative for studying an elastic solid by using FEM, providing for an orderly and systematic approach. Analytical mechanics is a useful numerical technique that allows for the generation of an adequate mathematical description via a set of alternative mathematical formulas. Because of the limitations that appear in the FEM model as a result of element correlation, the number of degrees of freedom (DOF) is significantly reduced; thus, analytical mechanics is the most common method used to describe such system. By analytic mechanics, the obtained formalism has a significant advantage because it provides a simple equations representation and providing easy application of classic FEM algorithms [2].

Voids are a type of manufacturing defect. It has been discovered that voids reduce the mechanical properties of the material. It is necessary to understand the impact of such voids on material mechanical properties, as well as to determine the acceptable range of the presence of this void in a polymeric material [2].

Only elastic states of the void micropolar bodies have been studied [33-34], but the dynamic response of this system studied in only one article [2], which only investigates the dynamic analysis of the polymer with void by using the FEM. In our study we will study both static and dynamic analysis of micropolar polymers with voids.

The organization of the rest of this article is as follows: the formulation of the problem and some basic notion in the FEM introduced in Sections 2. Sections 3 contains the kinematics, kinetic energy, potential energy, and work of different types of applied forces for a FRP with void defects. A section 3 includes the application of the Lagrange equations to get the 2nd-order differential equations for a 3D FE. Section 5 and 6 includes the results and conclusion about our study, respectively.

2. Formulation of the Problem

To perform the analysis, a polymer material with voids in an undistorted state has been used in this study.

The content of voids in FRP can be evaluated by using the following equation:

$$V_v = 1 - V_m - V_f \qquad (1)$$

where V_v, V_f and V_m are the content or volume fractions of void, matrix, and fiber in FRP, respectively.

The stiffness (E_s) formula for a solid material with spherical holes can be expressed as follows:

$$E_s = E_\rho (1 - V_v)^2 \qquad (2)$$

where the ρ and υ referred to non-porous and porous material, respectively and Vv refers the void content in composite.

The elastic modulus of unidirectional FRP composite with voids can be given by the following formula:

$$E_{i-v} = E_i (1 - V_v)^2 \qquad (3)$$

where E_i is the elastic constant of composite without voids .

The elastic modulus for matrix with voids as well as the theoretical value of elastic constant can be expressed by the following Eq. (4).

$$E_{m-v} = E_m(1 - V_{m-v})^2 \tag{4}$$

where E_{m-v} is the elastic modulus of the matrix containing voids, and V_{m-v} is the void content presented in the matrix, which can be given as follows:

$$V_{m-v} = \frac{V_v}{V_m} \tag{5}$$

The mass density of a matrix with voids can be determined according to Eq. 6:

$$v(x, y, z) = \rho(x, y, z)\, \gamma(x, y, z) \tag{6}$$

Where, $\boldsymbol{v}(x, y, z)$ is the mass density of the material with voids, $\boldsymbol{\rho}(x, y, z)$ refers to the mass density of the material without voids; $\gamma(x, y, z)$ refers to the volume fraction of material, where $0 < v \leq 1$ and it is a scale of change of volume in original material caused by compaction or distension of voids.

When the reference configuration is taken into account, the mass density can be estimated by Eq. 7.

$$v_o(x, y, z) = \rho_o(x, y, z)\gamma_o(x, y, z) \tag{7}$$

where (x,y,z) indicates to the arbitrary point M in the domain B, while (x_o,y_o,z_o) refers to B_o domain. Time is represented by the variable r, where $r \in [0, t_o]$. The range of Latin indices is the integers (1, 2, 3) while, (1, 2) is the range of Greek indices.

FEM is a classic, very well-developed method, with well-developed computer software, and it a powerful tool for determining the most engineering constants [35].

Euler-Lagrange equation method is commonly used for various types of materials in several engineering applications in the purpose of obtain their motion equations. Initially, a response to single finite element must be obtained. At this level, an arbitrarily chosen shape function was considered in this study. Relationships will be obtained in the local coordinate system, but using an appropriate transformation matrix, they can be transferred to a global frame of reference. The following step is to put together the obtained systems of equations to estimate the dynamic response of the model structure. By using the external applied loads on the elastic system and its boundary conditions, the solution of the differential equations can be obtained. It has been assumed that the deformations are small enough they have no effect on the mechanical system's general motion of the rigid body [2].

Another significant advantage is that the final form of the equations of motion does not include correlation forces. This is especially important in FEM, where typical system has a large DOFs value. It becomes useful to users when the application of this method results in a significant reduction in the number of unknowns, and thus the number of arithmetic operations [2,36].

3. Kinematics, kinetic energy, potential energy and work of a finite element

3.1. Kinematics

In this section, the 3D FE modeled as an elastic solid will be examined. The displacement of a given point of the studied solid is uniquely determined by a set of independent coordinates via the interpolation function in the FEM approximation. These coordinates might be nodal coordinates or its derivatives, or other kinematic sizes. The element will be linked to a movable coordinate frame. Finally, all FEs will be linked to the global coordinate system. A movement of the mobile reference system can be defined by angular velocity ($\overline{\omega}$ $(\omega_x, \omega_y, \omega_z)$), angular acceleration ($\bar{\varepsilon}(\varepsilon_x, \varepsilon_y, \varepsilon_z)$), velocity $\bar{v}_o(\dot{X}_o, \dot{Y}_o, \dot{Z}_o)$ and acceleration $\bar{a}_o(\ddot{X}_o, \ddot{Y}_o, \ddot{Z}_o)$ of the origin of the local reference system. All of these vectors are thought to be known. Two L and G indices will be used to demonstrate this because two reference systems (local and global) have been used in this study. Non-indexed sizes will be treated as if they were written in L (mobile reference) frame. Orthonormal operator [P] is used in rigid kinematics to change the components of a vector (r) from L (mobile) to G (fixed) reference frame [36]:

$$\{r\}_G = [P]\{r\}_L \tag{8}$$

When [P] is differentiated, the angular velocity and operator to vector ratio, as well as the angular acceleration operator to vector, are obtained [37].

Point M was considered to be belong to the elastic FE which will be M' after deformation which have a position vector $\{t_{M'}\}G$:

$$\{t_{M'}\}_G = [t_O]_G + [P](\{t\}_L + \{u\}_L) \tag{9}$$

where, $\{t_M\}G$ refers to the position vector of the point M, $\{t_O\}G$ is the position vector of the origin point O, and $\{u\}_L$ is the displacement vector. The continuous vector field of displacements is approximated in FEA by a linear relation of the type based on the independent coordinates of the FE [36]:

$$\{u\}_L = [S]\{N\}_L \tag{10}$$

where $\{N\}_L$ refers to the independent coordinates vector (shape function matrix). The velocity vector of M' can be expressed as follow:

$$\{v_{M'}\}_G = \{\dot{t}_{M'}\}_G = \{\dot{t}_O\}_G + [\dot{P}]\{t\}_L + [\dot{P}][S]\{N\}_L + [P][S]\{\dot{N}\}_L \quad (10)$$

, and acceleration vector:

$$\{a_{M'}\}_G = \{\ddot{t}_O\}_G + [\ddot{P}]\{t\}_L + [\ddot{P}][S]\{N\}_L + 2[P][S]\{\dot{N}\}_L + [P][S]\{\ddot{N}\}_L \quad (11)$$

When this vector becomes the local coordinate system they will be:

$$\{v_{M'}\}_L = [P]^P\{v_{M'}\}_G = \{\dot{t}_O\}_L + [P]^P[\dot{P}]\{t\}_L + [P]^P[\dot{P}][S]\{N\}_L + [S]\{\dot{N}\}_L \quad (12)$$

$$\{a_{M'}\}_G = [P]^P\{a_{M'}\}_G = \{\ddot{t}_O\}_L + [P]^P[\ddot{P}]\{t\}_L + [P]^P[\ddot{P}][S]\{N\}_L + 2[P]^P[\dot{P}][S]\{\dot{N}\}_L + [S]\{\ddot{N}\}_L \quad (13)$$

3.2. Kinetic energy

Because of its role as a prime integral, kinetic energy is an essential component in all formulations. Kinetic energy is expressed as follows in the investigated case:

$$E_c = \int_V \frac{1}{2}\rho\{v_{M'}\}_G^T\{v_{M'}\}G^{dV} \quad (14)$$

Kinetic energy can be defined in terms of global coordinates (G) as well. As a result, the transition of the independent coordinate vector $\{N\}L$ to the G system is known, and when it is done through [P] matrix, it will become $\{N\}_G$ [37]:

$$\{N\}_G = [P]\{N\}_L \quad (15)$$

We have too:

$$\{N\}_L = [P]^P\{N\}_G \quad (16)$$

Using equations (15) and (16), a new form of kinetic energy can be simply obtained. Clearly, the two kinetic energy expressions are equal. The following will make use of some notation:

$$ECv = \frac{1}{2}\{\dot{S}\}_L^P\left(\int_V [N]^P[Y][N]\rho_O dV)\right)\{\dot{S}\}_L \quad (17)$$

where [Y] is the matrix containing the coefficients of inertia.

3.3. Potential energy

Potential energy or internal work takes the following form:

$$E_p = \frac{1}{2}\int_V\{\sigma\}^P\{\varepsilon\}dV \quad (18)$$

Where {σ} contains the distinct component of the stress tensor and {ε} contains the distinct component of the strain's tensor. The relationship between strain and stress is obtained from Hooke law:

$$\sigma = [H]\{\varepsilon\} \quad (19)$$

The differential relations linking finite deformations and strains are as follow [37]:

$$\{\varepsilon\} = [b][S]\{N\} \quad (20)$$

Using (19) and (20) the internal work (18) becomes:

$$E_p = \frac{1}{2}\{N\}_L^P\left(\int_V[H]^P[b]^P[S]^P[b][S]dV\right)\{N\}_L \quad (21)$$

Simply, the traditional form of the potential energy can be as follow:

$$E_p = \frac{1}{2}\left(\int_V\{N\}_L^P[k]\{N\}dV\right) \quad (22)$$

Where

$$k = \int_V [H]^P[b]^P[S]^P[b][S]dV \quad (23)$$

3.4. Work

External mechanical work can be caused by two types of loads: volume forces $q = q(x, y, z)$ and concentrated forces acting in knots f_L . The concentrated forces f_L produce mechanical work as follows:

$$W^c = \{f\}_L^P\{N\}_L \quad (24)$$

, and the volume forces vector:

$$W = \{f\}_L^P \{N\}_L \quad (25)$$

$$W = \int_V \{p\}_L^P \{q\}_L dV = \left(\int_V \{p\}_L^P [S] dV\right)\{N\}_L = \{f^*\}_L^P \{N\}_L \quad (26)$$

3.5. Lagrangian

The typical form of Lagrangian (L) can be written as follow [38]:

$$L = E_c + E_p + W^c + W$$

Using Eq. (14), (22), (24), (26) it obtains:

$$L = \frac{1}{2}\int_V \rho\left(\{\dot{t}_O\}_L^P\{\dot{t}_O\}_L + 2\{\dot{t}_O\}_L^P[P]^P\{\dot{P}\}\{t\}_L + 2\{\dot{t}_O\}_L^P[P]^P\{\dot{P}\}[S]\{N\}_L + 2\{\dot{t}_O\}_L^P[S]\{N\}_L\right)dV + \frac{1}{2}\int_V \rho\left(\{t\}_L^P[\dot{P}]^P[\dot{P}]\{t\}_L + 2\{t\}_L^P[\dot{P}]^P[\dot{P}][S]\{N\}_L + 2\{t\}_L^P[\dot{P}]^P[\dot{P}][S]\{\dot{N}\}_L\right)dV + \frac{1}{2}\int_V \rho\left(\{N\}_L^P[\dot{P}]^P[S]^P[P][S]\{\dot{N}\}_L + 2\{\dot{N}\}_L^P[S]^P[\dot{P}]^P[S][P]\{\dot{N}\}_L + \{\dot{N}\}_L^P[S]^P[S]\{\dot{N}\}_L\right)dV - \frac{1}{2}\int_V \{N\}_L^P[k]\{N\}\,dV + \{f^*\}_L^P\{N\}_L + \{f\}_L^P\{N\}_L \quad (27)$$

4. Lagrange's equations

Lagrange equations applied for a FE is:

$$\frac{d}{dt}\left\{\frac{\partial L}{\partial \dot{d}}\right\}_L - \left\{\frac{\partial L}{\partial d}\right\}_L = 0 \quad (28)$$

The following equation is the final form of the equations of motion [2]:

$$([m] + [J] + [mv])\{\ddot{N}\}_L + [c]\{\dot{N}\}_L + ([k] + [k_v] + [k(\varepsilon)] + k(\omega^2)]\{S\}_L = \{q\}_L^P + \{f^*\}_L^P + \{f_v\}^P - [m_O^i]\{\ddot{t}_O\} - \{f^i(\varepsilon)\} - \{f^i(\omega^2)\}$$

5. Results

A bar of FRP with diameter of 16 mm and 300 mm in length was fixed at one of its ends and moved at its other end with a shear force and an axial force equal to 1 KN in order to demonstrate our method. It was assumed that the material contained 2% voids. FEM was used to study the static and dynamic analysis of FRP containing void defects. The results of stresses and displacements of FRP withiout and with void defects obtained in Fig. 1 and Fig. 2, respectively.

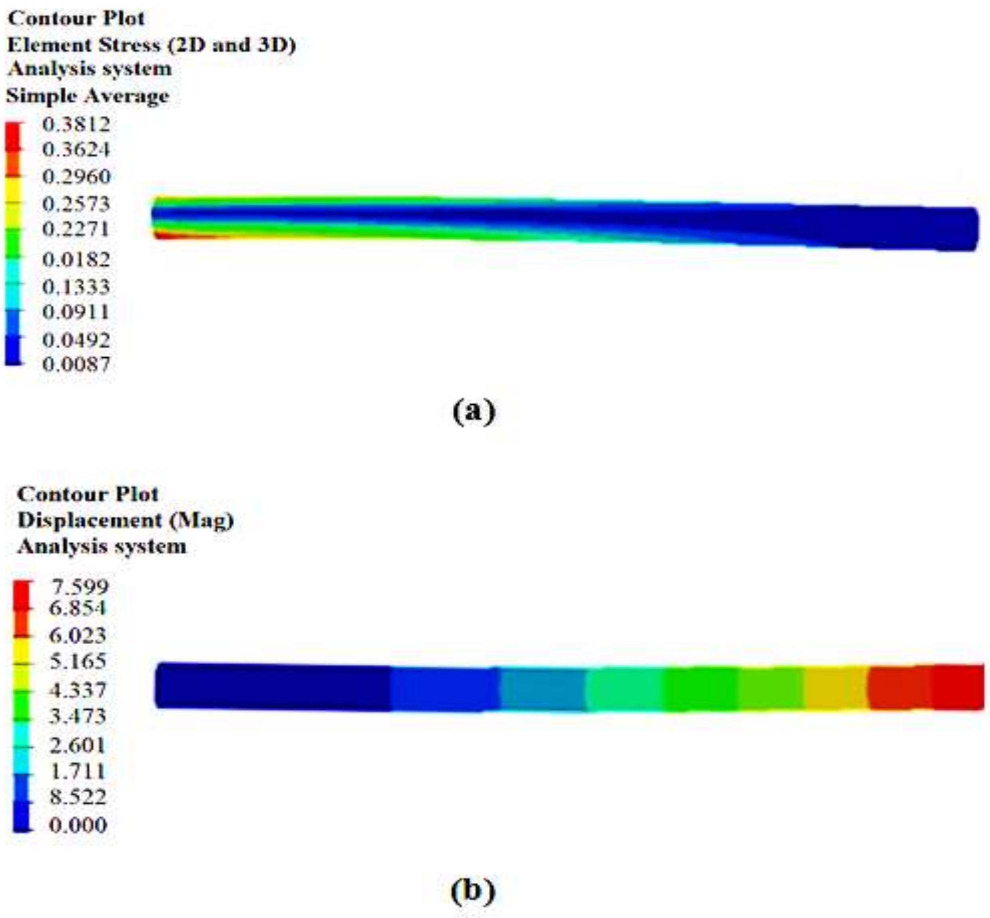
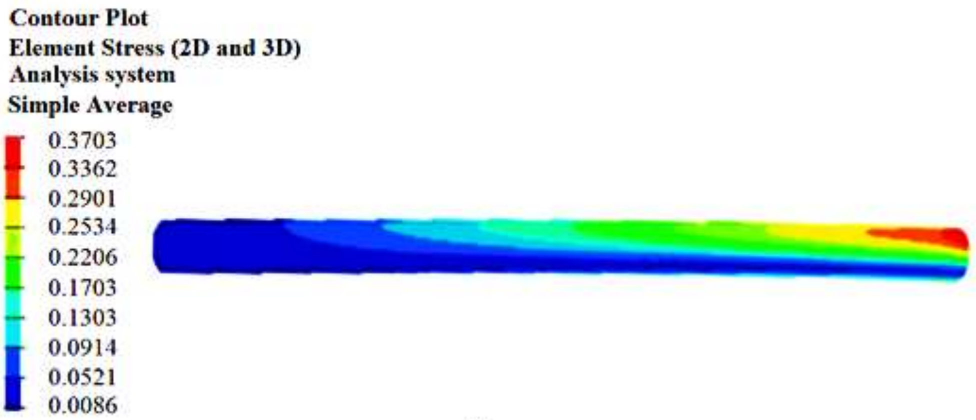
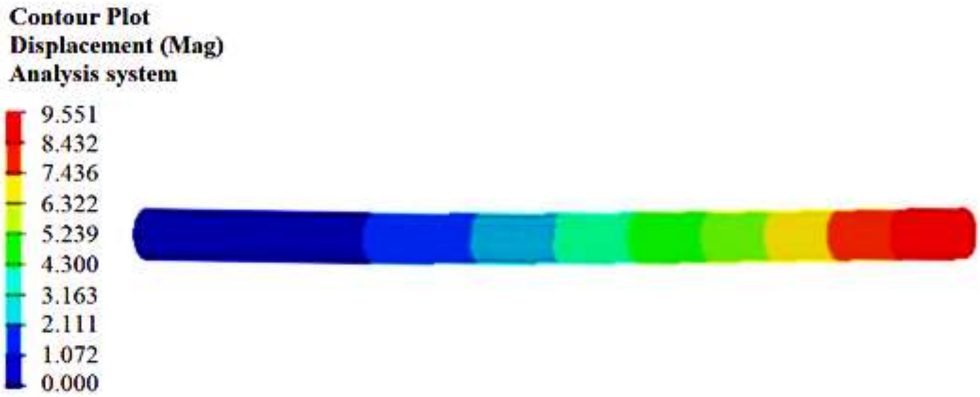


Figure 1. Material without void defects: (a) Stress (MPa); (b) Displacement (mm)



(a)



(b)

Figure 2. Material with void defects: (a) Stress (MPa); (b) Displacement (mm)

The mechanical properties of the matrix reduced due to the presence of voids, stress between adjacent fibres cannot be optimally transferred to the matrix. As a result, when the matrix contains voids, the maximum stress reduction is observed under each loading. Furthermore, we can see that stress concentrations are primarily influenced by the direction of loading, not only in the void condition but also in the non-void condition. In the case of a void-free composite, the stress is primarily distributed throughout the matrix. The stress is primarily distributed on one side of a composite containing voids.

6. Conclusions

According to our study, the following conclusions are as follow:

The writing of equations of motion is the most important step in approaching a multibody system (MBS) with elastic void materials. This stage necessitates a thorough understanding of the elastic properties of these materials as well as the constitutive laws. The other steps which so-called the assembly of the equations of motion. It will be calculated using the normal procedures used in common software of FEM after the equations of motion have been obtained.

The Euler-Lagrange equation method has several advantages, including: homogeneous writing, the ability to automate intermediate stages, and the formal use of potential energy, kinetic energy, and mechanical work.

When a high viscosity resin is used in manufacturing, void defects are likely to appear in the material. This is due to the difficulty of a high viscosity resin penetrating and clogging all of the voids between fibres. When the fibre concentration is extremely high, these voids becomes extremely difficult and can't be avoided. It is clear that the presence of such voids has become inevitable, As a result, voids must be considered when performing calculations, because the presence of such voids can have a significant impact on the material's mechanical properties.

References

[1] Schmauder, Siegfried; Chen, Chuin-Shan; Chawla, Krishan K.; Chawla, Nikhilesh; Chen, Weiqiu; Kagawa, Yutaka (2019). Handbook of Mechanics of Materials || Characterizing Mechanical Properties of Polymeric Material: A Bottom-Up Approach. , 10.1007/978-981-10-6884-3(Chapter 5), 57–91. doi:10.1007/978-981-10-6884-3_5

[2] Vlase, S., & Marin, M. (2021). Finite Element Method-Based Dynamic Response of Micropolar Polymers with Voids. Polymers, 13(21), 3727. doi: 10.3390/polym13213727

[3] Carlsson, L. A., & Du, E. (2018). Water uptake in polymer composites with voids. In Durability of Composites in a Marine Environment 2 (pp. 33-57). Springer, Cham.

[4] Chu, Y., Sun, L., Yang, X., Wang, J., & Huang, W. (2021). Multiscale simulation and theoretical prediction for the elastic properties of unidirectional fiber-reinforced polymer containing random void defects. Polymer Composites. doi: 10.1002/pc.26028

[5] Luo, L., Zhang, B., Lei, Y., Zhang, G., Zhang, Z., Meng, B., & Liu, Z. (2021). Identification of voids and interlaminar shear strengths of polymer-matrix composites by optical microscopy experiment and deep learning methodology. Polymers for Advanced Technologies, 32(4), 1853-1865. doi: 10.1002/pat.5226

[6] Gladysz, G. M., & Chawla, K. K. (2020). Voids in materials: from unavoidable defects to designed cellular materials. Elsevier.

[7] Mehdikhani, M., Gorbatikh, L., Verpoest, I., & Lomov, S. V. (2019). Voids in fiber-reinforced polymer composites: A review on their formation, characteristics, and effects on mechanical performance. Journal of Composite Materials, 53(12), 1579-1669. doi : 10.1177/0021998318772152

[8] Little JE, Yuan XW, Jones MI (2012) Characterisation of voids in fibre reinforced composite materials. Ndt&E Int 46:122–127

[9] ASTM D2734, Standard test methods for void content of reinforced plastics (2009) ASTM International, West Conshohocken

[10] Carlsson LA, Adams DF, Pipes RB (2014) Experimental characterization of advanced composite materials. CRC Press, Boca Raton

[11] Ling Liu; Bo-Ming Zhang; Dian-Fu Wang; Zhan-Jun Wu (2006). Effects of cure cycles on void content and mechanical properties of composite laminates. , 73(3), 303–309. doi: 10.1016/j.compstruct.2005.02.001

[12] Bodaghi, M., Cristóvão, C., Gomes, R., & Correia, N. C. (2016). Experimental characterization of voids in high fibre volume fraction composites processed by high injection pressure RTM. Composites Part A: Applied Science and Manufacturing, 82, 88-99. doi: 10.1016/j.compositesa.2015.11.042

[13] Saenz-Castillo, D., Martín, M. I., Calvo, S., Rodriguez-Lence, F., & Güemes, A. (2019). Effect of processing parameters and void content on mechanical properties and NDI of thermoplastic composites. Composites Part A: Applied Science and Manufacturing, 121, 308-320. doi: 10.1016/j.compositesa.2019.03.035

[14] Zhang, D., Heider, D., & Gillespie Jr, J. W. (2017). Void reduction of high-performance thermoplastic composites via oven vacuum bag processing. Journal of Composite Materials, 51(30), 4219-4230. doi:10.1177/0021998317700700

[15] Pishvar, M., Amirkhosravi, M., & Altan, M. C. (2019). Magnet assisted composite manufacturing: A novel fabrication technique for high-quality composite laminates. Polymer Composites, 40(1), 159-169.

[16] Yalcinkaya, M. A., Sozer, E. M., & Altan, M. C. (2017). Fabrication of high-quality composite laminates by pressurized and heated-VARTM. Composites Part A: Applied Science and Manufacturing, 102, 336-346.

[13] Tai, J. H., & Kaw, A. (2017). Transverse shear modulus of unidirectional composites with voids estimated by the multiple-cells model. Composites Part A: Applied Science and Manufacturing, 105, 310-320. doi: 10.1016/j.compositesa.2017.11.026

[14] Hyde, A., He, J., Cui, X., Lua, J., & Liu, L. (2020). Effects of microvoids on strength of unidirectional fiber-reinforced composite materials. Composites Part B: Engineering, 187, 107844. doi: 10.1016/j.compositesb.2020.107844

[15] Mekonnen, A. A., & Woo, K. (2020). Effects of defects on effective material properties of triaxial braided textile composite. International Journal of Aeronautical and Space Sciences, 21(3), 657-669.

[16] M. Mehdikhani, N. A. Petrov, I. Straumit, A. R. Melro, S. V. Lomov, L. Gorbatikh, Compos. Part. A. Appl. Sci. Manuf. 2019, 117, 180.

[17] Alharbi, A. M. (2021). Two temperature theory on a micropolar thermoelastic media with voids under the effect of inclined load via three-phase-lag model. ZAMM - Journal of Applied Mathematics and Mechanics / Zeitschrift Für Angewandte Mathematik Und Mechanik. doi:10.1002/zamm.202100078

[18] Goodman, M.A.; Cowin, S.C. A continuum theory for granular materials. Arch. Ration. Mech. Anal. 1972, 44, 249–266.

[19] Wang, Panding; Lei, Hongshuai; Zhu, Xiaolei; Chen, Haosen; Fang, Daining (2018). Investigation on the mechanical properties of epoxy resin with void defects using digital image correlation and image-based finite element method. Polymer Testing, 72, 223–231. doi: 10.1016/j.polymertesting.2018.10.025

[20] Hayashi, T., & Takahashi, J. (2017). Influence of void content on the flexural fracture behaviour of carbon fiber reinforced polypropylene. Journal of Composite materials, 51(29), 4067-4078.

[21] Dong, C. (2016). Effects of process-induced voids on the properties of fibre reinforced composites. Journal of Materials Science & Technology, 32(7), 597-604.

[22] Shen, T.F. Void damage model and service life prediction for solid high polymer. Chin. Sci. Bull. 2001, 46, 1842–1845.

[23] Summerscales, J.; Fry, S.A. Poisson ratio in fiber-reinforced polymer composites with a high void content. J. Mater. Sci. Lett. 1994, 13, 912–914.

[24] Wu, Y.N.; Shivpuri, R.; Lee, L.J. Effect of macro and micro voids on elastic properties of polymer composites. J. Reinf. Plast. Compos. 1998, 17, 1391–1402.

[25] Hocine, N.A.; Hamdi, A.; Zairi, F. Experimental and finite element investigation of void nucleation in rubber-like materials. Int. J. Solids Struct. 2011, 48, 1248–1254.

[26] Soria, M.H.A.; Aramaki, R.T.; Viviani, E. Experimental Determination of Void Size Curves. In Proceedings of the 1st International Conference on Geo-Filters: Filters in Geotechnical and Hydraulic Engineering, Karlsruhe, Germany, 20–22 October 1992; pp. 43–48.

[27] Sivaneshan, P.; Harishankar, S. Experimental Study on Voided Reinforced Concrete Beams with Polythene Balls. In Proceedings of the International Conference on Civil Engineering and Infrastructural Issues in Emerging Economies (ICCIEE), Thanjavur, India, 17–18 March 2017; p. 80.

[28] He, H.Y. Microscopic Mechanism Analysis and Experimental Study of Void beneath Slab. International Conference on Automation, Communication, Architectonics and Materials. Adv. Res. Autom. Commun. Architecton. Mater. 2011, 225, 692–696.

[29] Wu, Y.T.; Liu, T.; Yang, K.J. Experimental study on detection of void in concrete pavement slab by FWD. In Proceedings of the 6th International Conference on Energy Materials and Enviroment Engineering, Tianjin, China, 24–26 April 2020; p. 508.

[30] Bao, J.Q.; Ji, Z.H.; Yang, Q. Approximation of the effective moduli of particulate composite with the fixed grid finite element method. Finite Elem. Anal. Des. 2014, 78, 1–7.

[31] Park, H.; Lee, S.W. Cure simulation of thick composite structures using the finite element method. J. Compos. Mater. 2001, 35, 188–201.

[32] Xiong, X.; Shen, S.Z.; Hua, L.; Liu, J.Z.; Li, X.; Wan, X.; Miao, M. Finite element models of natural fibers and their composites: A review. J. Reinf. Plast. Compos. 2018, 37, 617–635.

[33] Yu, Y.L.; Ye, J.R.; Wang, Y.; Zhang, B.M.; Qi, G.C. A mesoscale ultrasonic attenuation finite element model of composites with random-distributed voids. Compos. Sci. 2013, 89, 44–51.

[34] Rinivasulu, G.; Velmurugan, R.; Jayasankar, S. Influence of void microstructure on the effective elastic properties of discontinuous fiber-reinforced composites. J. Compos. Mater. 2015, 49, 2745–2755.

[35] Katouzian, M., Vlase, S., & Scutaru, M. L. (2021). Finite Element Method-Based Simulation Creep Behavior of Viscoelastic Carbon-Fiber Composite. *Polymers*, *13*(7), 1017.

[36] Vlase, S., Negrean, I., Marin, M., & Scutaru, M. L. (2020). New analytical formalisms used in finite element analysis of robots with elastic elements. Journal of Taibah University for Science, 14(1), 1335-1341.

[37] Vlase S, Dănăşel C, Scutaru ML, et al. Finite element analysis of a two-dimensional linear elastic systems with a plane “rigid motion. Rom. Journ. Phys. 2014;59(5–6):476–487

[38] Vlase S. Elimination of Lagrangian multipliers. Mech Res Commun. 1987; 14:17.