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Advanced Composite Materials and Structures

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Composite materials are used to produce multi-objective structures such as fluid reservoirs, transmission pipes, heat exchangers, pressure vessels due to high strength and stiffness to density ratios and improved corrosion resistance. The mathematical concepts can be used to simulate and analyze the generated mechanical and thermal properties of composite materials regarding to the desired performances in actual working conditions. To solve and obtain the exact solution of the developed nonlinear differential equations in the composite materials, analytical methods can be applied. Mechanical and thermal analysis of complex composite structures can be numerically analyzed using the Finite Element Method (FEM) to increase performances of composite structures in different working conditions. To decrease failure rate and increase performances of composite structures under complex loading system, thermal stress and effects of static and dynamic loads on the designed shapes of composite structures can be analytically investigated. The stresses and deformation of the composite materials under the complex applied loads can be calculated by using the FEM method in order to be used in terms of safety enhancement of composite structures. To increase the safety level as well as performances of the composite structures in different working conditions, crack development in elastic composites can be simulated and analyzed. To develop and optimize the process of composite deigning in terms of mechanical as well as thermal properties under different mechanical and thermal loading conditions, the advanced machine learning systems can be applied. A review in recent development of composite materials and structures is presented in the study and future research works are also suggested. Thus, to increase performances of composite materials and structures under complex loading systems, advanced methodology of composite designing and modification procedures can be provided by reviewing and assessing recent achievements in the published papers.

1 Introduction

New materials created by combining two or more constituent materials on a macroscopic scale are named composite materials. In order to provide new thermal and mechanical behavior regarding to the complex loading systems of working conditions, two or more materials are mixed together as composite materials [1]. Composite materials are now more popular in the aerospace and automotive industries due to their excellent qualities, such as high strength-to-weight ratios, high specific

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stiffness, corrosion resistance and low coefficient of thermal expansion (CTE) in certain directions. Chemical compatibility, wettability, adsorption properties, and the creation of complicated stress states arising from changes in heat and moisture expansion are all unknown features of composite materials [2]. The composite materials have exceptional mechanical and structural qualities, including a high strength-to-weight ratio, resistance to fire, chemicals, corrosion, and wear, as well as low manufacturing costs [3]. As a result, advanced materials by considering the applied mechanical and thermal loads of working condition are produced as composite materials which are specially designed to carry out a certain function, such as becoming stronger, lighter, or electrically resistant [4]. Also, stiffness and strength of produced composite materials can be enhanced in terms of composite designing process using combination of different materials [5]. The composite materials are preferred over conventional materials in different working conditions as qualities and thermal and mechanical properties are enhanced [6].

Steel bars, which are strong in tension, are inserted to a concrete beam's weak tensile portion in order to enhance tensile resistance of concreate. As a result, composite materials are designed and employed for specific requirements such as construction sector and aeronautical engineering in order to provide appropriate performance under complex loads of actual working condition [7]. To provide superior mechanical and thermal qualities than original materials, composite materials should be designed to resist such events as impact loading, vibrational loading, delamination, cracking, and fatigue. Each composite material attribute must be evaluated and measured, preferably in real time and in a real-world setting, although this is not always practicable [8]. Ceramic matrix composites (CMCs), metal matrix composites (MMCs), intermetallic matrix composites (IMCs), carbon-carbon composites (CCCs), and polymer matrix composites are among the various subgroups of artificially manufactured composites based on the kind of matrices and reinforcement (PMCs). Classification of composite materials is shown in the figure 1.

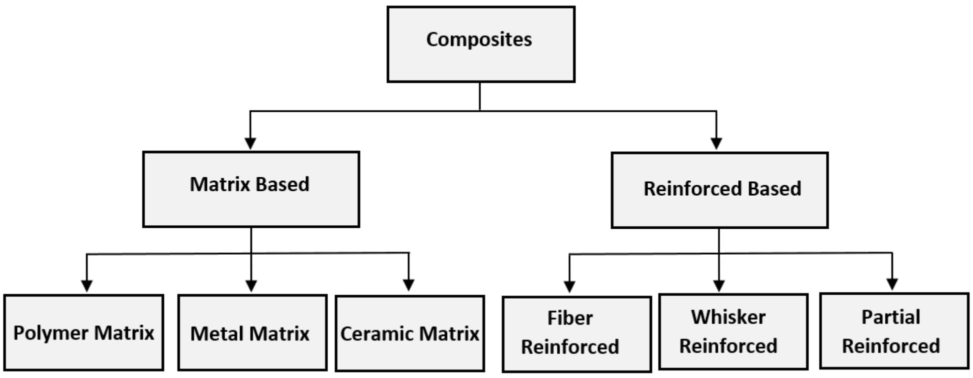

Fig. 1 – Classification of composite materials.

Young's modulus is a fundamental material characteristic in different applications in terms of designing process of composite material [9]. Also, fire resistance, fatigue life, vibrations and harmonic load resistance, and joinability are considered in terms of composite materials designing [10]. Other ranking features, such as the mechanism of material failure, ductile collapse, brittle failure should also be considered once the material has been formed into a composite structure [11]. The mechanical, thermal and functional qualities of composite are related to the composite structures and elements which are analyzed during designing process of composite material [12]. Accurate material property data is required in terms of designing and developing of the composite materials in different industrials applications in order to provide appropriate performance under complex loads of actual working condition. As a result, nonlinear differential equations are used in order to simulate and analyze the mechanical as well as thermal behavior of composites components in actual working conditions. The analytical methods can be applied to the developed nonlinear differential equations in order to obtain the closed forms of exact solutions of the equations. As a consequence, by solving the nonlinear differential equations of mechanical and thermal properties of composite materials, the safety and reliability of manufactured components using composite materials can be improved [13].

To measure the delamination in composite materials, the optimal position of electrodes is numerically obtained by Kovaļovs et al. [14]. To simulate and analyze the intralaminar and translaminar fracture in long fiber composite materials, application of the predictive numerical methods is investigated by Quintanas-Corominas et al. [15]. Numerical forming of continuous fibre reinforced composite material is reviewed by Bussetta and Correia [16] to present the recent development in the numerical solutions of the composite components. numerical modeling and evaluation of the multi-directional matrix composite architectures is reviewed by Ghatage et al. [17] to study on multi-directional functionally graded beam, plate, and shell architectures. The flexure behavior of pultruded GFRP deep beams as well as damage evaluations was investigated experimentally and theoretically by Madenci et al. [18] to provide the Kinetic, macro and micro mechanical damage analyzes of the composite components. Numerical Analysis and experimental validation of Natural Fiber (Luffa) reinforced polymer composite frequency and deflection responses is implemented by Bisen et al. [19] to obtain the impact of a key design parameter on the Luffa fiber-reinforced composite structure. Based on a pair stress-based shell model, nonlinear oscillation of compound conical microshells with in-plane variability are observed by Yuan et al. [20] to evaluate and obtain the influence of couple stress size in the composite conical microshells.

Buckling and free vibration assessments of pultruded GFRP laminated composites were investigated experimentally, statistically, and mathematically by Madenci et al. [21] to obtain the mechanical properties of the obtained pultruded of the composite specimens. The discrete singular convolution technique was used by Civalek and Baltacıoğlu [22] to study the vibration of carbon nanotube reinforced composite (CNTRC) annular sector plates. The effective material properties in magneto-electro-elastic composite materials is numerically obtained by Sladek [23] et al. to analyze the particle size effects on the mechanical properties of composite parts. To obtain the heat conduction in composite cylindrical shells, exact solution of the modified differential equation is presented by Rahmani et al. [24]. Crack analysis of isotropic solids and anisotropic composites by using the numerical methods is implemented by Kang et al. [25] to obtain the mechanical behavior of the composite structures under dynamic loads. To develop the production methods of composite parts using forming process, numerical forming of continuous fibre reinforced composite material is reviewed by Bussetta and Correia [16]. To analyze and modify the mechanical behavior of thin-walled laminated composite parts under statics loads, numerical method is implemented by Günay and Timarci [26]. To prevent part failure due to thermal warping, numerical analysis of large-scale thermoplastic polymer composites is investigated by Compton et al. [27].

Mechanics of multifunctional composite materials and structures is reviewed by Gibson [28] to develop the performances of composite materials in complex loading systems. Polymer composite materials is reviewed by Hsissou et al. [29] to analyze and enhance mechanical and thermal properties of the polymer composite structures in actual working conditions. The impact resistance of composite materials is reviewed by Cantwell and Morton [30] in order to analyze and enhance the dynamic response and resistance of fibre-reinforced composite structures under dynamics loading systems. Micromanufacturing process of composite materials is reviewed by Hasan et al. [31] to enhance the quality of produced parts from composite materials. In order to analyze and enhance quality of composite structures, Non-destructive testing and evaluation of composite materials and structures is reviewed by Wang et al. [32]. Micro and nanocellulose in polymer composite materials is reviewed by Omran et al. [33] to enhance performances of polymer composite materials under complex loading systems. To enhance the resistance of the fiber-reinforced composite materials under complex loads of actual working conditions, the response of fiber-reinforced polymer matrix composite materials under transient impact loading is reviewed by Andrew et al. [34]. Recent advances in fabrication of non-isocyanate polyurethane-based composite materials are reviewed by Stachak et al. [35] to enhance chemical, and physical properties of produced structures from the polyurethane-based composite materials under different loading systems.

Functionally graded materials (FGMs) are the heterogeneous composite materials which progressively changes in composition/constituents and/or microstructures along one or more spatial directions, resulting in a gradual change in characteristics and functions that may be adjusted for improved performance [36]. Review on analysis of functionally graded structures is presented by Boggarapu et al. [37] to analyze and develop the selection of materials, processing techniques and analytical modelling and applications of FGMs in different industries. An overview of manufacturing methods, applications and future challenges in FGMs materials is presented by Saleh et al. [38] to develop the procedures of designing and production of FGMs materials.Tthe manufacturing processes of functionally graded materials is reviewed by Parihar et al. [39] in order to analyze and develop the production process of manufactured part from the FGMs materials. Additive manufacturing of metal-based functionally graded materials is reviewed by Reichardt et al. [40] in order to achieve a continuous structure between a wide range of selected combinations of alloys.

The Homotopy Perturbation Method is used by Nourazar et al. [41] to obtain the exact solution of Newell-Whitehead-Segel Equation. To obtain the exact solution of the Burgers-Huxley as well as Fitzhugh–Nagumo non-linear differential equations, application of the Homotopy Perturbation Method is investigated by Nourazar et al. [42, 43] .The Variational Iteration Method and Homotopy Perturbation Method are used by Soori and Nourazar [44] in order to obtain the exact solution of nonlinear differential equations. To obtain the exact solution of nonlinear differential equation The variational iteration method and the homotopy perturbation method to the exact solution of the Fisher Type Equation is presented by Soori et al. [45]. The Variational Iteration Method and the Homotopy Perturbation Method to the Exact Solution of the generalized Burgers-Fisher Equation is used by Soori [46] in order to obtain the exact solution of nonlinear differential equation. To present the capabilities of the semi analytical methods in obtaining the exact solution of nonlinear differential equation, a Comparison between the Variational Iteration Method and the Homotopy Perturbation Method for the Burgers-Huxley Equation is presented by Soori [47]. The variational iteration method is used by Soori et al. [48] to obtain the exact solution of the Newell-Whitehead-Segel Equation. Also, the variational iteration method is used by Soori [49, 50] in order to Solve the Korteweg-de Vries-Burgers Equation and Fitzhugh–Nagumo non-linear differential equations. To obtain the series solution of the Weakly-Singular Kernel Volterra Integro-Differential Equations, the Combined Laplace-Adomian Method is used by Soori [51].

Soori et al. provide virtual machining methodologies to assess and improve CNC machining in virtual worlds [52-55]. Soori et al. provides a review of current developments in friction stir welding techniques to investigate and enhance effectiveness in the process of component manufacturing employing welding procedures [56]. Soori and Asamel have explored implementations of virtual machining systems to reduce deflection error and residual stress throughout turbine blade five-axis milling processes [57]. Soori and Asmael created implementations of virtualized machining system in evaluating and reduction of cutting temperature throughout milling operations of hard to cut components [58]. Soori et al. proposed an improved virtual machining method to improve surface properties throughout five-axis milling operations of turbine blades [59]. Soori and Asmael devised virtual milling techniques to reduce deflection error during five-axis milling processes of impeller blades [60]. Soori and Asmael provided a summary of existing developments from published articles in order to examine and improve the parameter optimization technique of machining processes [61]. Dastres et al. give a study of Radio Frequency Identification (RFID) based wireless manufacturing systems to improve energy utilization efficiency, data quality and availability across the supply chain, and precision and dependability during the component production process[62]. Machine learning and artificial intelligent in CNC machine tools is reviewed by Soori et al. [63] in order to enhance productivity and added value in component manufacturing processes using CNC machining operations.

Soori and Arezoo [64] presented a review in residual stress to assess and decrease residual stress during machining processes. To minimize surface integrity and residual stress during grinding operations of Inconel 718, optimized machining parameters using the Taguchi optimization approach is presented by Soori and Arezoo [65]. To increase cutting tool life during machining operations, different methods of tool wear prediction is studied by Soori and Arezoo [66]. Computer aided process planning is reviewed by Soori and Asmael [67] in order to enhance productivity in process of part manufacturing. Developments in web-based decision support systems is presented by Dastres and Soori [68] in order to build decision support systems for data warehouse operations. Dastres and Soori [69] presented a review of current research and uses of artificial neural networks in a variety of disciplines, including risk analysis systems, drone control, welding quality analysis, and computer quality analysis to develop the application of artificial neural networks in performance enhancement of engineering products. In order to decrease the effects of technology development to the natural disaster, Dastres and Soori [70] discussed the use of information and communication technology in environmental conservation. To enhance security in the networks and web of data, secure socket layer is presented by Dastres and Soori [71]. Advances in web-based decision support system is reviewed by Dastres and Soori [72] in order to develop the methodology of decision support systems by analyzing and suggesting the gaps between presented techniques. To enhance security measure in networks, a review in recent development of network threats is presented by Dastres and Soori [73]. Advanced image processing systems is reviewed by Dastres and Soori [74] to develop the capabilities of image processing systems in different applications.

In the research work, a review in recent development of numerical simulation and modification of composite materials is presented in order to provide the recent development from the published papers in the analysis and modification of composite materials and structures. As a result, advanced methodology of the composite simulation and modification can be presented in order to increase the performances of composite materials and structures under complex loading systems.

2 Mechanical Properties of Composite Materials

The strength of composites is determined by elements such as the brittleness or ductility of inclusions, as well as the ductility of matrix. Mechanical properties of multi-layered structure as composite materials can be acutely simulated by using the mathematical equations. Stiffness matrices from the structure properties due to applied forces can be obtained in order to be analyzed by using the numerical methods [75]. Additional layer of matrix can be considered in terms of mathematical modelling of the composite materials in order to analyze the mechanical properties of new design of the generated composites for the special purposes. As a result, longitudinal Young Modulus and standard deviation of new deigned composite can be accurately obtained using numerical solutions. Moreover, the thickness imperfection to achieve the desired mechanical properties of composite parts under special conditions of loads and working can be accurately calculated by using numerical methods [76].

The choice of failure criteria in composite parts plays an important role in terms of designing new composite materials. So, the durability of manufactured parts from composites should be presented by the designers in order to provide safety as well as suitable usage of composites in structures. In comparison to metal, predicting fatigue life in composite materials is more difficult [77]. This is due to the fact that failure in composite materials does not result from the spread of a single macroscopic break. Fiber breakage and matrix cracking, debonding, transverse-ply cracking, and delamination take place interactively in composite components subjected to repeating loads, and the predominance of one or the other may greatly affect both materials characteristics and testing circumstances. So, it is important to analyze and predict the fatigue behavior of composite materials due to repeating loads conditions in order to increase safety level of manufactured components [78].

In the fiber reinforced composites which are composed of fibers embedded in matrix material, the effects of length and directions of the fibers on the mechanical properties of the campsites can be numerically investigated. As a result, the new kind of composite materials regarding the different working conditions can be generated [79]. Also, in the particulate composites, the volume and density of fraction occupied by inhomogeneities particles, and the interfaces between the components can generate the mechanical properties such as brittleness or ductility of the composites [80].

The process of polymer composite reinforcements by using fibers, fabrics particles or whiskers to increase mechanical capacities of new composites can be numerically analyzed in order to increase the efficiency in the process [81]. The orientation as well as volumes of the fiber in the polymer matrixes reinforcements process can be analytically analyzed in order to increase the strength and flexibility of new generated composites. So, the optimized process of polymer composite reinforcements can be numerically obtained in terms of quality enhancement of produced composites [82]. To prevent part failure due to the fatigue crack propagation in the composite materials and structures produced by additive manufacturing processes, the numerical methods can be implemented. As a result, the mathematical models of fatigue crack propagation in the surface and deep of additive manufacturing composites structures can be analytically solved in order to prevent the part failure and increase safety factor in the working conditions [83].

Different frictional contact conditions in polymer and metal matrix composites can be numerically investigated in order to obtain the wear and frictional behavior of composites during contact mechanics. The influence of fiber volume fraction, fiber orientation, fiber length and sliding orientation to the distribution of contact traction can be numerically investigated to increase the wear resistance in the contact mechanism [84]. So, the contact magnitudes and their distribution over the contact zone can be accurately predicted by solving the nonlinear differential equations of composite contact problems using numerical methods [85].

The effects of composite material's orientation to the strength and stiffness of anisotropic composites such as silica fibers in a pure aluminum matrix can numerically investigated in order to increase the mechanical capacities of the components in the toleration of applied loads [86]. Strength, fracture toughness and stiffness of metal matrices composites can be numerically investigated in order to increase the capacities of load tolerating by the composites [87]. Flexibility of polymers composites as thermosets and thermoplastics composites due to static as well as dynamic loads can be simulated by using nonlinear differential equations. Instability, rigidity, toughness and ability to repudiate creep during working conditions of thermoplastic composites can be numerically analyzed in order to increase mechanical capacities of polymers composites [86]. As a result, the exact solutions of the problem can increase the safety level of the thermosets and thermoplastics composites by increasing flexibility capacities and decreasing the failure rate of the components during the static and dynamic loads [88].

To analyze and study the instability and safety of anisotropic composite beams under static loads, the Timoshenko and Euler-Bernoulli beam equations can be used. As a result, the exact analytical solutions in closed form can be obtained in order to increase the deflections and deformation capacities of composite beams. To obtain the differential equations for Timoshenko beam, the principle of virtual work is used [89].

$$F' + \bar{F} = 0 \tag{1}$$

$$M' + eF + \bar{M} = 0 \tag{2}$$

where, F is applied force and M is moments to the composite beam. As a result, the expression for the vector of rotations θ can be obtained as [89],

$$\theta = K_D e \iiint \bar{F} dxdxdx - K_B^T \iint \bar{F} dxdx - K_D \iint \bar{M} dxdx - \frac{1}{2} K_D e C_1 x^2 + (K_B^T C_1 + K_D C_2)x + C_3 \tag{3}$$

Also, the vector of the displacements u can be obtained as,

$$u = -eK_D e \iiint \bar{F} dxdxdx + (K_B e + eK_B^T) \iiint \bar{F} dxdxdx - K_A \iint \bar{F} dxdx +$$
$$eK_D \iiint \bar{M} dxdxdx - K_B \iint \bar{M} dxdx + \frac{1}{6} eK_D e C_1 x^3 \tag{4}$$
$$-\frac{1}{2}\big((K_B e + eK_B^T)C_1 + eK_D C_2\big)x^2 + (K_A C_1 + K_B C_2 - eC_3) + C_4$$

So, the Eqs. (3) and (4) as differential equations for Timoshenko beam can be used in terms of instability analysis of composite beams under the static loads. Moreover, the fully coupled Euler-Bernoulli composite beam in a compact matrix form can be written as [89],

$$-\mathrm{A}u'' + \mathrm{B}w''' = \bar{M} \tag{5}$$

$$-B^T u''' + Dw^{(IV)} = \bar{F} \tag{6}$$

where u is axial displacement, w is out-of-plane bending; F is the functions non-uniformly distributed loads different directions. As a result, integral form for static displacements of a fully coupled Euler-Bernoulli composite beam are presented as,

$$u = -K_A \iint \bar{M} dxdx - K_B \iiint \bar{F} dxdxdx + \frac{1}{2} A^{-1} \bar{M} C_1 x^2 + C_5 x + C_6 \tag{7}$$

$$W = K_B^T \iiint \bar{M} dxdx + K_D \iiint \bar{F} dxdxdx + \frac{1}{6} C_1 x^3 + \frac{1}{2} C_2 x^2 + C_3 x + C_4 \tag{8}$$

By using the numerical methods, the closed forms of the exact solutions of the presented Eqs. (3), (4), (7) and (8) can be accurately obtained in order to provide instability analysis of composite beams under static loads.

To simulate the linear and nonlinear heat conduction, elasticity, and functionally graded composite layered materials by using mathematical concepts, the Helmholtz-type elliptic partial differential is studied. A bi-material composed of two subdomains Ω_1 and Ω_2, with boundaries $\partial\Omega_1$ and $\partial\Omega_2$ and heat transfer coefficients (wave numbers) K_1 and K_2 is considered. So, the temperature distribution due to acoustic pressure in each subdomain satisfies the Helmholtz-type equations as [90],

$$\nabla^2 u_1 \pm K_1^2 u_1 = 0 \quad in\ \Omega_1 \tag{9}$$

$$\nabla^2 u_2 \pm K_2^2 u_2 = 0 \quad in\ \Omega_2 \tag{10}$$

Then, the modified Helmholtz equation with a minus sign in Eqs. (11) and (12), subject to the boundary conditions cab be presented as,

$$u_1 = f_1 \quad on\ {}^{\partial\Omega_1}/_{\Gamma_{12}} \tag{11}$$

$$u_2 = f_2 \quad on\ {}^{\partial\Omega_2}/_{\Gamma_{12}} \tag{12}$$

As a result, the Helmholtz equation in composite materials when Ω_1 is a bounded obstacle and $\Omega_2 = {R^n}/{\Omega_1}$ is its exterior unbounded complement can be presented as Eq. (13) [90],

$$u_1 - (u_2 + u^{inc}) = 0 \quad on\ \Gamma_1$$

$$u_1 - (u_2 + u^{inc}) = -i\eta \frac{\partial(u_2 + u^{inc})}{\partial n_2} \quad on\ \Gamma_2 \tag{13}$$

$$\kappa \frac{\partial u_1}{\partial n_1} + \frac{\partial(u_2 + u^{inc})}{\partial n_2} = 0 \quad on\ \partial\Omega_1$$

where, κ represents the ratio between the material electric permittivity of Ω_1 and Ω_2, Γ_1 and Γ_2 are two disjoint portions of the boundary $\partial\Omega_1$ such that $\Gamma_1 \cap \Gamma_2 = \emptyset$ and $\Gamma_1 \cup \Gamma_2 = \partial\Omega_1$, η is the impedance coefficient allowing for non-perfect contact, and u^{inc} is the incident field given by a plane wave moving in the unit direction.

3 Thermal Properties of Composite Materials

Effective thermal conductivity reflects the ability of a material in order to conduct heat in terms of applied thermal loads to the composite structures. The rate of thermal energy storage and conversion is an important factor of composite designing process in order to decrease the possibility of thermal failure of composite components in actual working conditions [91]. The service temperature of composites in various heating regimes is determined by the melting point, physical, and mechanical properties of the composite at various temperatures [92]. So, the thermal stability and melting behavior of composites can be determined by analysis of thermal properties of composite materials using differential equations. The problem of heat conduction in the metal matrix composite of Titanium, Aluminum and magnesium materials can be analytically investigated in order to analyze the temperature distribution in the composite components [93]. Thus, the thermal fractures of metal matrix composite, particle and fiber reinforced composites parts in actual working condition can be prevented to increase safety and reliability of produced components using composite materials [94].

The problem of heat conduction in composite materials can be analytically investigated in order to analyze the temperature distribution in a composite cylindrical vessel under physical conditions [95]. Thus, the thermal fractures of composite parts in actual working condition can be prevented to increase safety and reliability of produced components using composite materials. The geometry and boundary conditions of composite cylindrical vessel is shown in the figure 2.

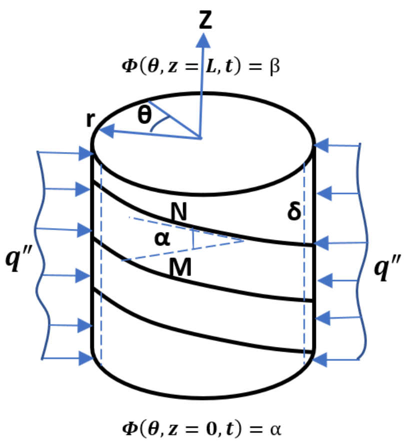

Fig. 2 – The geometry and boundary conditions of composite cylindrical vessel.

The Fourier series of conductive heat transfer for present composite cylindrical shell in a cylindrical coordinate system can be written as [96],

$$\begin{Bmatrix} q_\theta \\ q_z \end{Bmatrix} = -\begin{bmatrix} \overline{K_{11}} & \overline{K_{12}} \\ \overline{K_{21}} & \overline{K_{22}} \end{bmatrix} \begin{Bmatrix} \frac{\partial T}{\partial \theta} \\ \frac{\partial T}{\partial z} \end{Bmatrix} \tag{14}$$

where q_θ and q_z represent the heat fluxes in θ and z directions, respectively, $[\overline{K}]$ is the conductive coefficient in the off-axis coordinate, and r is the radius of the cylindrical shell. The heat conduction equation in differential equation can be achieved as [89],

$$\frac{\overline{K_{11}}}{r^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\overline{2K_{12}}}{r}\frac{\partial^2 T}{\partial z \partial \theta} + \overline{K_{22}}\frac{\partial^2 T}{\partial z^2} - \frac{h(T-T_\infty)}{\delta} + \frac{q'' + u'''\delta}{\delta} = \rho c_p \frac{\partial T}{\partial t} \tag{15}$$

The fractional change in length of a body when heated or cooled over a certain temperature range is known as linear thermal expansion which usually presented as coefficient per unit temperature of the materials. In order to provide an accurate designing procedure for thermal conductivity of composite materials, the thermal coefficients of the designed composite materials should be obtained [97]. Heat transfer problem and effective thermal conductivity coefficient of matrix composite materials can also be accurately calculated using the numerical solutions in the simulated nonlinear differential equations of the composite materials [98]. The Rosen and Hashin as well as Chamberlain differentials equations are presented in order to accurately obtain the thermal expansion coefficients of composites using numerical methods [99].

3.1 Equation of Rosen and Hashin

To express the upper and lower bounds on effective thermal expansion coefficients of composites, Rosen and Hashin [100] developed the Eq. (16) as,

$$\begin{aligned} \alpha_1 = \widehat{\alpha_1} + \left(S_{11} - \widehat{S_{11}}\right)\left[\left(\alpha_{f1} - \alpha_{m1}\right)P_{11} + \left(\alpha_{f2} - \alpha_{m2}\right)2P_{12} + \left(S_{12} - \widehat{S_{12}}\right)\left(\alpha_{f2} - \alpha_{m2}\right)2P_{12} \right. \\ \left. + \left(\alpha_{f2} - \alpha_{m2}\right)2\left(P_{22} + P_{23}\right)\right] \\ \alpha_2 = \widehat{\alpha_2} + \left(S_{12} - \widehat{S_{12}}\right)\left[\left(\alpha_{f1} - \alpha_{m1}\right)P_{11} + \left(\alpha_{f2} - \alpha_{m2}\right)2P_{12}\right] + \left(S_{22} - \widehat{S_{22}}\right)\left[\left(\alpha_{f1} - \alpha_{m1}\right)P_{12} + \right. \\ \left. \left(\alpha_{f2} - \alpha_{m2}\right)\left(P_{22} + P_{23}\right)\right] + \left(S_{23} - \widehat{S_{23}}\right)\left(\alpha_{f1} - \alpha_{m1}\right)P_{12} + \left(\alpha_{f2} - \alpha_{m2}\right)\left(P_{22} + P_{23}\right) \end{aligned} \tag{16}$$

where, the terms *S* and *P* includes material property data and terms with and without a hat refer to volume average and effective composite properties respectively.

3.2 Equation of Chamberlain

To obtain the thermal expansion coefficients of composites, Chamberlain presented the Eq. (17) as [101],

$$\alpha_2 = \alpha_m + \frac{2\left(\alpha_{f2} - \alpha_m\right)v_f}{v_m(F - 1 + v_m) + \left(F + v_f\right) + \frac{E_m}{E_{f1}}\left(1 - v_{f12}\right)\left(F - 1 + v_m\right)} \tag{17}$$

where α_{f2} is the thermal expansion coefficient of fiber in the transverse direction, v_{f12} is the Poisson ratio of the fiber and *F* is a packing factor which accounts for fiber packing geometry, and is equal to 0.9069 for hexagonal packing and for 0.7854 for square packing respectively [101]. When the difference in thermal expansion coefficients between fiber and matrix is combined with a temperature step during composite production, complicated mechanisms of differential shrinkage can emerge. So, the thermal residual stresses caused by shrinking must be considered in any stress analysis of the composite structure [102]. The heat parameters for newly designed composite structures can be numerically calculated using the exact solutions of the developed nonlinear differential equations for the heat behavior of composite structures. Any kind of complex composite structure where the heat conduction problem is analyzed, can be considered as the grid of resistors in complex components. So, the thermal analysis of composite materials can increase the safety level of produced components from the composite by decreasing the part failure due to thermal fracture [103].

Creep over an extensive range of temperature during working conditions of thermoplastics composites can be considered in order to increase the failure load as well as creep resistance in the composite components in high temperature working conditions [104]. Moreover, shrinkage and the tendency of the shape change in the thermoplastics composites can be numerically investigated in order to retain its original form and shape during actual working conditions [105]. The influence of particle size in the particulate composites to the thermal conductivity of composite components can be numerically investigated in order to analyze the heat resistance of new designed composites [106]. Also, the effects of thermal shock on the mechanical properties of the composite materials can be analytically investigated in order to increase safety levels of produced components form the composites [107].

3.3 Coefficients of thermal expansion in composite structures

The thermal expansion of uniform linear objects is proportional to temperature change across narrow temperature ranges. Thermal expansion is beneficial in the creation of thermometers using bimetallic strips, but it can cause internal stress when a structural element is heated and held at a constant length. The fractional change in length of a body during heating or cooling over a certain temperature range is known as the coefficient of thermal expansion (CTE), and it is commonly expressed as a coefficient per unit temperature interval at a given temperature. It's an important material feature, especially when working with a composite construction in a temperature-changing environment [108]. Although other criteria like as the kind of filler, resin, and degree of conversion are clearly essential, filler content was a substantial role in preventing CTE [109].

An empirical investigation for the thermal expansion coefficient of composite multi-layered flaky gun propellants is presented to obtain the effect of lamination and coating on thermal expansion [110]. To simulate the composite damage caused by thermal expansion mismatch, a 3D discrete element technique was used [111]. Mn3Zn0.7Ge0.3N /Al composites that have negligible thermal expansion at room temperature is studied to accurately obtain the coefficients of thermal expansions [112]. Controlled thermal expansion of ceramic composites is studied to obtain the exact numbers of the coefficients of thermal expansion using the dilatometer and precision impedance analyzer [113]. To present a new way to developing light-weight constructions, large positive, zero, and negative heat capacity in three-dimensional lightweight microstructures of the composite structures are studied [114].

4 Elastoviscoplastic Behavior of Composite Materials

For elastoviscoplastic composite materials, an incremental-secant mean-field homogenization approach with second statistical moments was developed [115]. The elastoviscoplastic response of long fibre composites utilizing functionally graded interphases was studied using micromechanics in order to obtain the elastoviscoplastic behavior of composite materials at the moderate strain rates [116]. For dominant failure analysis of composite laminates exposed to varying strain rate loadings, a consistent elastoviscoplastic damage model was developed in order to analyze the failure of the composite structures exposed to varying strain rates of loading [117]. In order to anticipate the stress–strain response for various fibre orientation angles, an invariant-based elastoviscoplastic description for unidirectional polymer composites at the finite stress is proposed [118]. To analyze the elastoviscoplastic behavior of polymer- and metal-matrix composites reinforced by spheroidal elastic particles, incremental variational procedure is implemented [119]. To predict the nonlinear behavior of an unknown material at different strain rates and temperatures elastoviscoplastic behaviour of polyurethane foam at various strain rates and temperatures was modelled [120]. Based on the translated field approach, an affine formulation for self-consistent modelling of elastoviscoplastic heterogeneous materials is implemented in order to study the behaviour of heterogeneous materials subjected to complicated thermomechanical loading routes [121].

5 Mechanical Behavior of Composite Structures

5.1 Fracture Problems in Composite Materials

The effects of cracks and imperfections on the impact strength of polymer components affect the idea of fracture of polymeric materials, and the critical length of a crack is a major determinant in fracture strength. The fracture toughness of a material is determined by two factors in failure concepts: the first is stress intensity, and the second is energy [122]. Meanwhile, the stress intensity variable defines fracture toughness (Kc) and links crack size to fracture strength, while the energy variable indicates critical energy released (Gc), which is connected to the energy expended to propagate Leaves on the surface [123]. Matrix cracking, fiber breaking, delamination across distinct plies, fiber deboning, and shear-driven fracture are all common failure mechanisms [124]. The degradation of the resin matrix and/or the contact between the filler and the resin matrix is the most common cause of failure in resin composites [125]. Numerical solutions for delaminated graphite-epoxy composites under uniform axial extension are provided to demonstrate the underlying nature of delamination fracture behavior. The greater the particle size in epoxy composites filled with aluminum trihydrate powder, the higher the fracture toughness, although there is an ideal value for particle volume fraction that reduces fracture toughness in larger quantities [126]. Fibre compressive damage and crack propagation is shown in the figure 3 [126] .

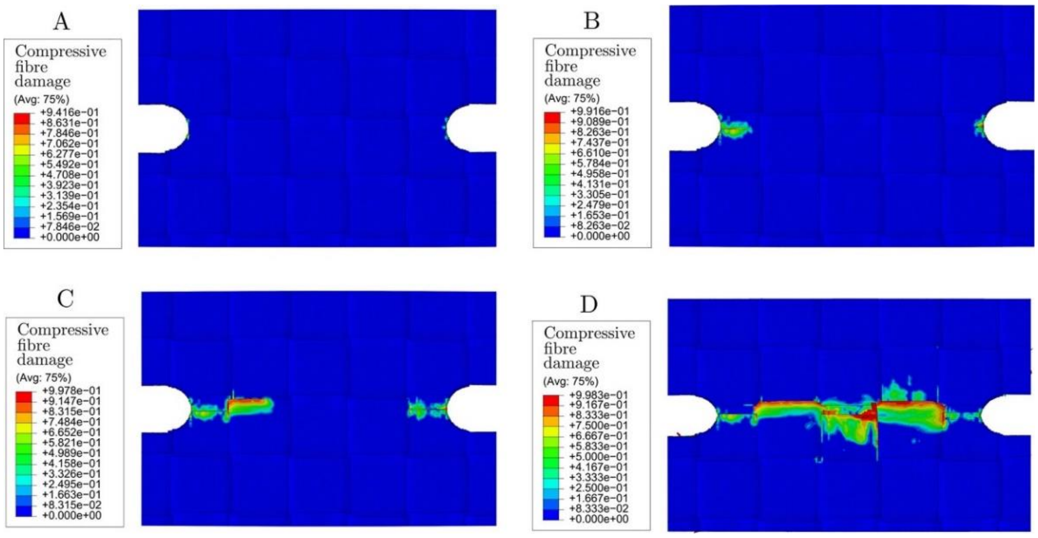

Fig. 3 – Fibre compressive damage and crack propagation [126].

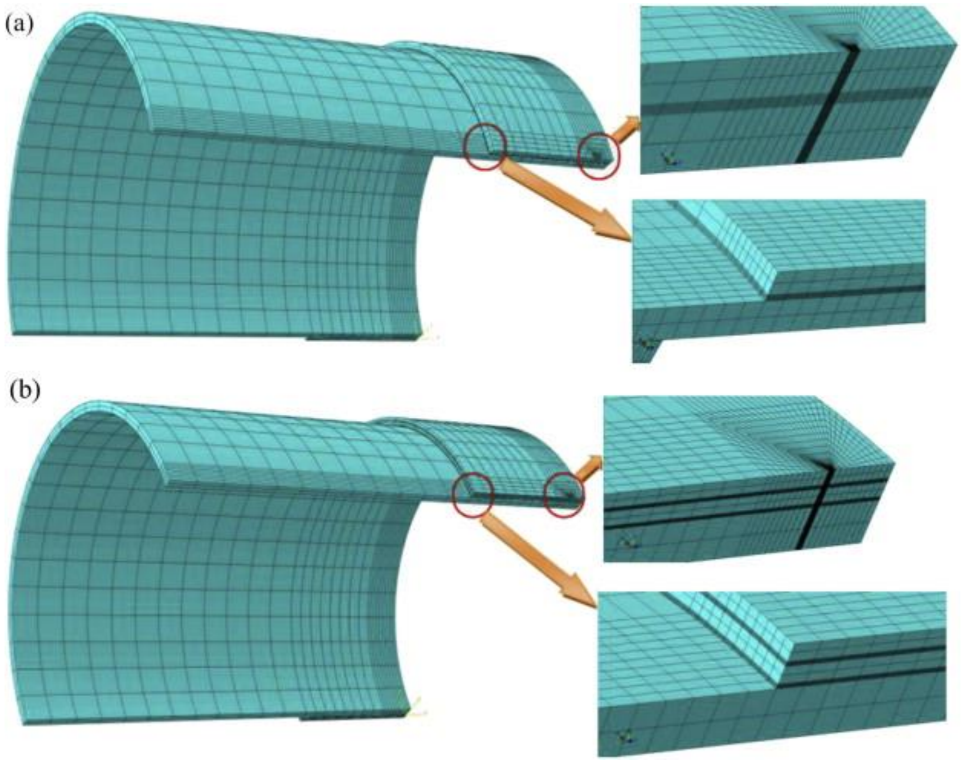

Fig. 4 – Mesh and finite element analysis of 1/4 pipeline with longitudinal crack [135].

The failure process of composites with homogeneous isotropic materials is different because they are non-isotropic. In fact, failure in non-isotropic materials can be caused by different states of stress [127]. In the study of the failure of composites, the behavior of each layer is investigated. Whenever the stress distribution causes a layer to fail, the failure calculations continue by removing that layer [128]. Many factors are involved in studying the failure of composites, the most important of which are the thickness of the composite, the direction of the fibers, the composition of the layers, its mechanical properties and its thermal properties [129].

5.2 Crack development in elastic composites

Cracking elastic composites is a frequent material degradation induced by stress, which can be exacerbated by various variables such as corrosion, fatigue, high pressure, and building material. Matrix cracking is a common pattern of composite material failure. A crack in the matrix might occur during production or during loading [130]. To forecast damage in continuous fiber ceramics matrix composites under transverse tension, The crack band approach is implemented [131]. An analytical approach for microannulus cracks developed around a wellbore is implemented in order to provide advanced fiber failure analysis in composite materials production [132]. Under uniaxial compression, mechanical characteristics and fracture development of double-layer composite rock-like specimens with two parallel fissures is presented in order to analyze crack evolution behavior under the loads [133]. Based on strain dissipations, an analytical technique for fracture detection of glass fiber reinforced polymer–sea sand concrete composite systems is presented to accurately predict the fracture and cracking behaviors of composite structures [134]. Finite element analysis of the integrity of an API X65 pipeline with a longitudinal crack repaired with single- and double-bonded composites is presented by Meriem-Benziane et al. [135] to predict and prevent the crack creation in composite pipelines under different loading condition. Mesh and finite element analysis of 1/4 pipeline with longitudinal crack is shown in the figure 4 [135].

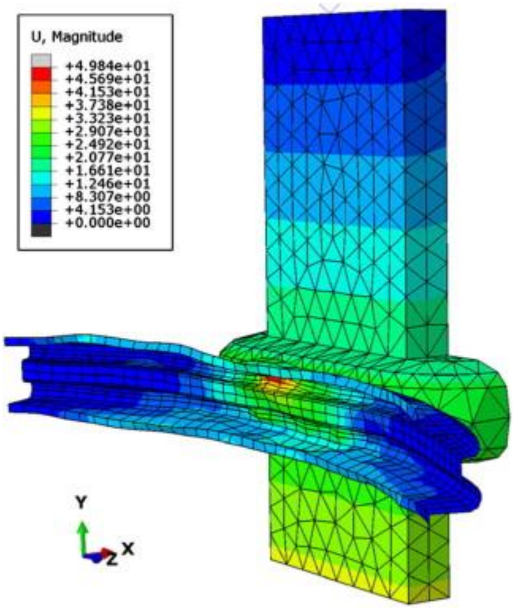

Fig. 5 – Displacement profile of double hat profile after impact [142].

5.3 Delamination problems of composite materials

In the aerospace and automotive industries, composite laminate is widely used. As a result, delamination, one of the most common and difficult failure modes, has prompted much study and the fast development of both modeling and experiment methods [136, 137]. Damage from the development of such delamination causes a reduction in strength, toughness, and fatigue life [138]. Low velocity caused delamination of composite structures, which is one of the key issues in the safety analysis of the composite structures. Matrix cracking, bending fractures, and shear cracks all contribute to delamination [139]. Visual examination, tap testing (sounding), ultrasound, radiography, and infrared imaging are all nondestructive testing procedures for detecting delamination in structures. Delamination at the surface and edges of materials can be detected through visual examination [140]. Drilling operations of thick composites without delamination is studied in order to enhance the strength of the composite structure [141]. Selection process of the best geometrical bumper beam concept to fulfill the safety parameters of the defined product design specification using the bio-composite material is presented by Davoodi et al. [142] to enhance resistance of composite bumper beam under dynamics loads. Displacement profile of double hat profile after impact using finite element method is shown in the figure 5 [142]. Effects of various parameters on strength and ductility of Biomimetic layered fiber-reinforced Ti–Al composites through finite element analysis is presented by Chen and Hao [143] to simulate and enhance specific bending strength and fracture bending strain under the complex loading system. The stress-strain curve, plastic strain and damage variable of the L-3LFR composite structure is shown in the figure 6 [143].

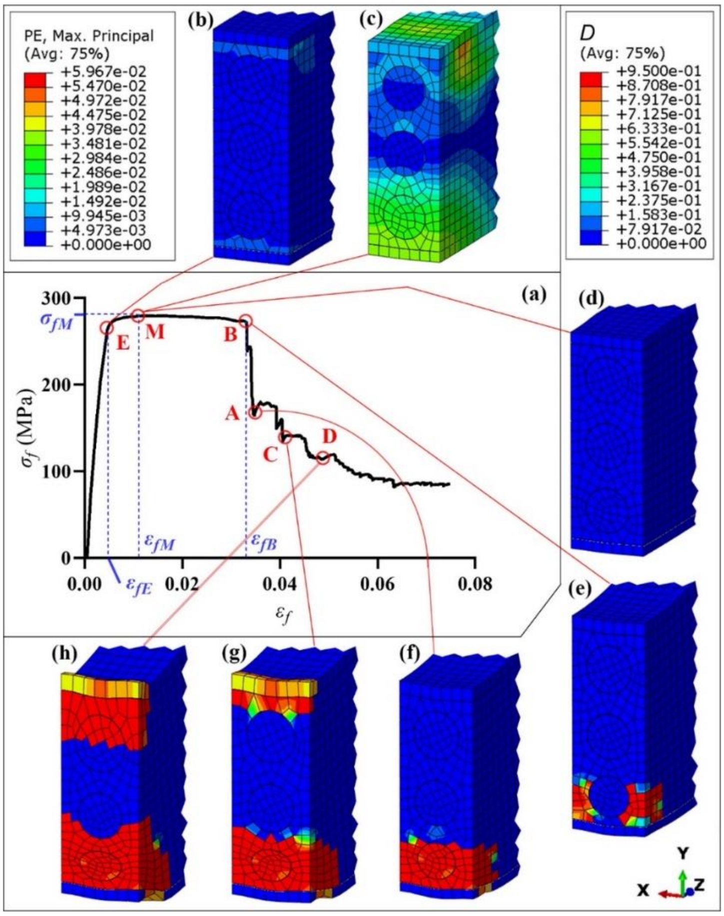

Fig. 6 – The stress-strain curve, plastic strain and damage variable of the L-3LFR composite structure [*143*].

5.4 Stress concentrations in composite materials

A stress concentration factor is a dimensionless metric for determining how concentrated the stress is in a mechanical component. It's the difference between the greatest stress in the component and a reference stress. All known structural components have stress concentrations. Stress concentrations are extremely crucial since they are frequently the cause of failure [144, 145]. The effect of dental remnants and restorative materials on stress distribution and concentration is studied in order to extend the working life of composite dental implants in real-world situations [146]. Simulation and fatigue performance of short fiber reinforced polymer composites due to the stress concentration factors is reviewed to increase safety factors in the composite joints [147]. Voxel and consistent meso-scale models of woven composites are compared in order to obtain the stress concentrations effects in composite structures [148]. The Finite Element Method (FEM) analysis was used in order to design reinforced curvilinear fibres composite structures by considering the effects of stress concentration factors in actual working conditions [149]. Methods for predicting failure of composite multi-bolt joints using characteristic length measuring method is presented in order to decrease the effects of stress concentration in the composite structures [150]. To model composite tensile failure of the composite structures in actual working conditions, stress concentration analysis using the floating node approach is implemented [151].

6 Numerical Simulation of Composite Structures using Finite Element Method

To simulate the mechanical properties of composite materials such as young modulus and standard deviation, strength and flexibility, instability, rigidity, toughness and ability to repudiate creep during working conditions can be simulated by using the numerical simulation [152]. The mathematical equations of thermal as well as mechanical properties of the composite materials can be used in the finite element simulation of the composite pipes under internal pressure and bending moments [153]. Also, fatigue life as well as fatigue crack propagation in composite materials due to repeated or varying load can be accurately predicted using numerical methods in order to increase the working life of produced parts from composite materials [154]. Thus, the safety and stability of the designed composite beams under the different loads can be increased by providing numerical simulation of the composite structures in the virtual environments [155]. Evolution of curing residual stresses in composite materials using multi-scale method is presented by Yuan et al. [156] to calculate and decrease the micro-scale residual stresses by using the results of macro-scale simulations. Micro residual stresses distribution after curing process of representative volume element model is shown in the figure 7 [156].

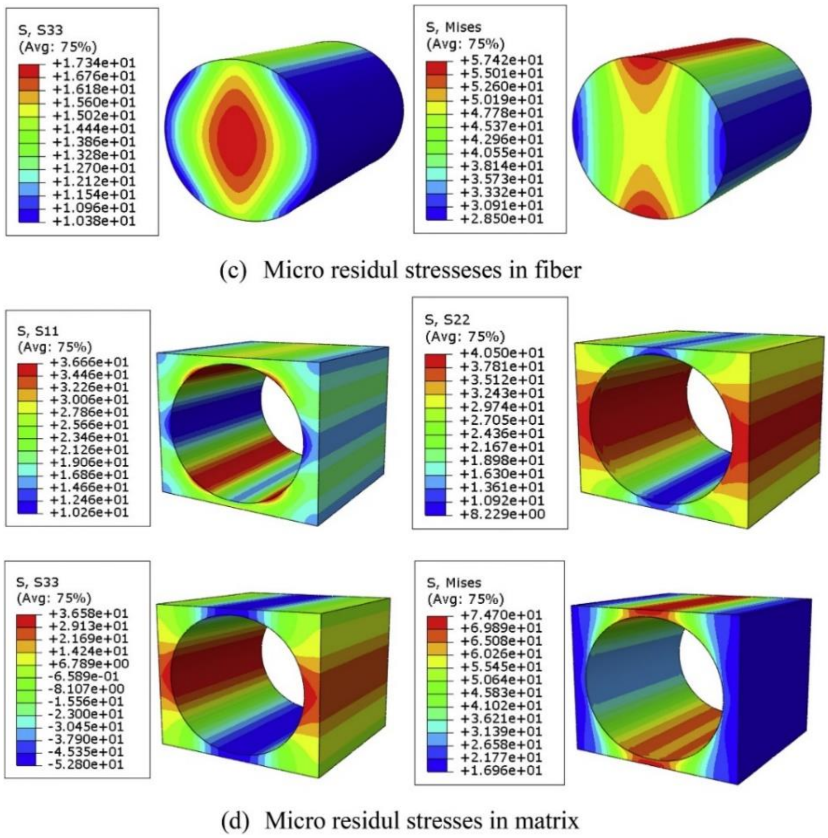

Fig. 7 – Micro residual stresses distribution after curing process of representative volume element model [*156*].

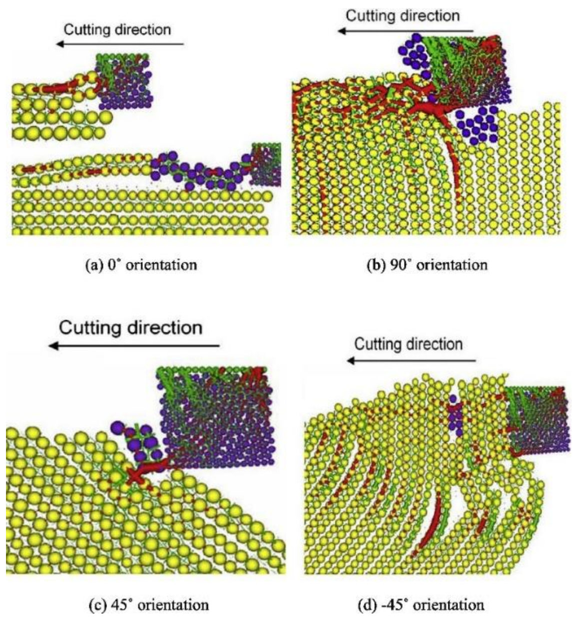

***Fig. 8 – The formation of a chip during orthogonal cutting using discrete element simulation for various fiber orientations* [158].**

To get the mean value, coefficient of variation, and probability distribution in the designed composite structures, a material microstructure-based stochastic finite element analysis of composite structures is proposed [157]. A discrete element method for the simulation of carbon fiber-reinforced polymer cutting operations is presented to simulate chip formation and cutting forces during machining operations of composite materials [158]. Figure 8 depicts the formation of a chip during orthogonal cutting using discrete element simulation for various fiber orientations. Free vibration analysis of laminated FG-CNT reinforced composite beams using finite element method is presented in order to increase strength as well as safety levels in the composite structures [159]. An improved inverse finite element approach for multi - layered composite and sandwich structure movement and stress management is presented to provide the sophisticated composite structures with precise form and stress sensing [160]. A pheno-numerical modelling technique for predicting process-induced distortions is developed in order to accurately predict and minimize the distortion in the composite structures in composite manufacturing process [161].

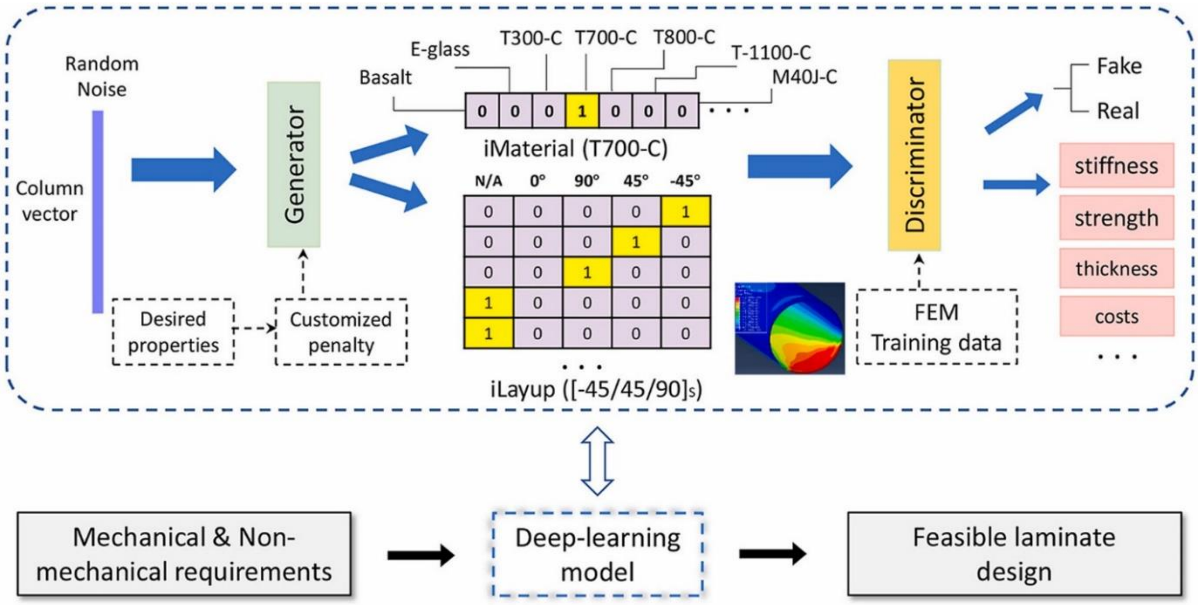

Fig. 9 – The procedure of developed deep learning method in designing and modification of composite materials [165].

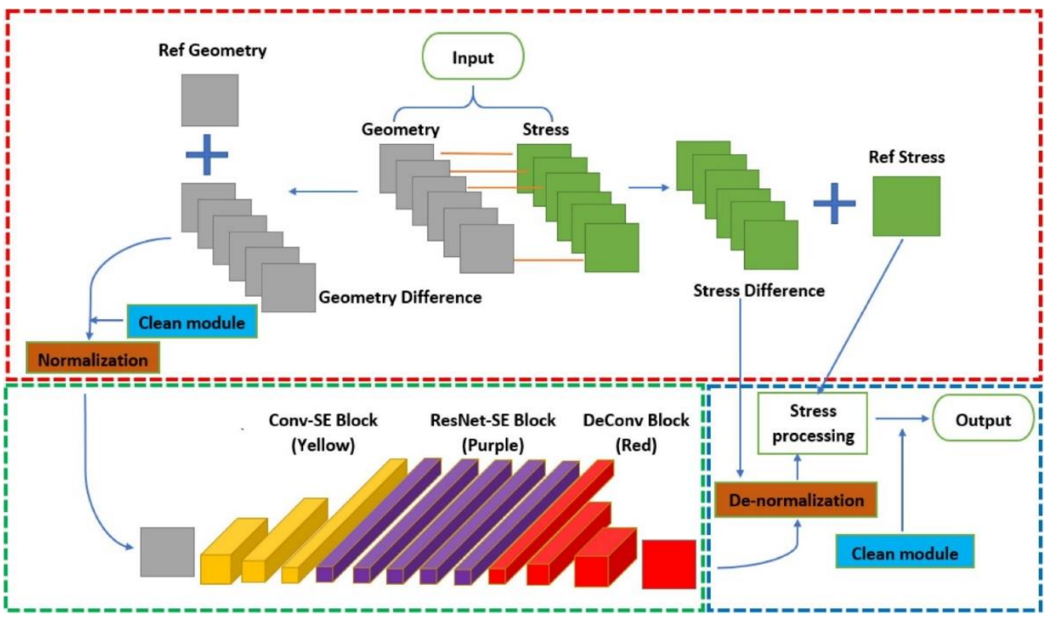

Fig. 10 – Difference-based Neural Network (DiNN) structure [*171*].

7 Machine Learning Methods in Analysis and Modification of Composite Materials

Machine learning (ML) has been hailed as a potential method for developing and discovering new materials for a variety of applications. In the design of composite structures, ML techniques may be used to design and optimize composites for the next generation of materials with exceptional characteristics [162, 163]. Five machine learning models as fully connected neural network (FCNN) model, a deep neural network (DNN) model, a radial basis function (RBF) neural network model, a support vector regression (SVR) model and a K-nearest neighbors (KNN) model are used for predicting the uniformity of a composite's degree of cure in an autoclave [164]. In order to present appropriate solutions for several design boundaries in of during designing process of composite materials, Qiu et al. [165] proposed a deep learning-based composite design technique in order to achieve the targets such goal strength, maximum deformation, minimal thickness, and lowest cost. The procedure of developed deep learning method in designing and modification of composite materials is shown in the figure 9 [165].

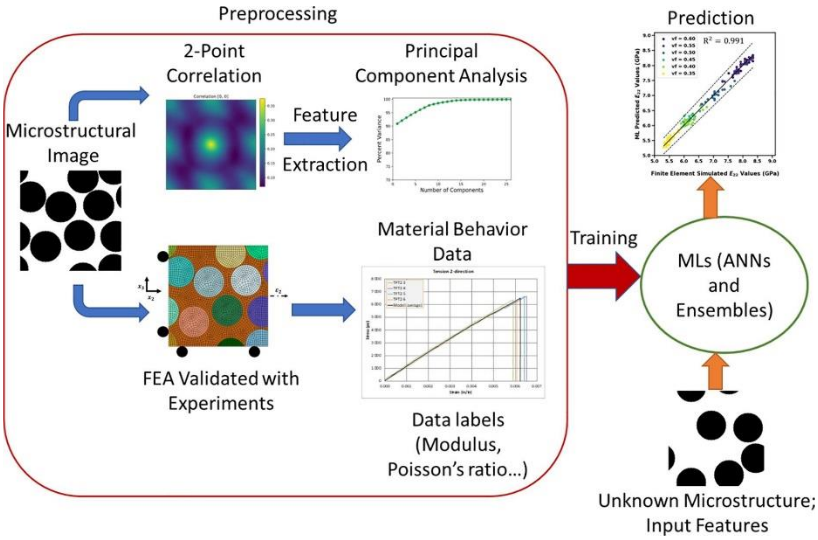

Fig. 11 – The machine learning modeling framework of the study [*172*].

Also, Machine learning algorithms are used to predict damage progression in composite materials [166]. In high-contrast composite materials, machine learning algorithms for elastic localization connections is implemented in order to increase the safety factor of the elastic composites structures under complex loads [167]. Elastic localization in three-dimensional composite microstructures modeled using machine learning approach is presented in order to improve computing efficiency and increase the parallelism of model training in the composite designing process [168]. Microstructure optimization and material design using predictive machine learning methodology is proposed in order to increase the performances of designed composite structures for the different purposes [169]. Machine learning approaches were used to predict the shear strength and behavior of RC beams enhanced with externally bonded FRP sheets [170]. The FEM analysis are widely used in designing and analysis of heterogeneous media stress in composite materials and built-up materials. However, in cases of optimization and multi-scaling, where several design iterations should be evaluated repeatedly until convergence, finding stress distributions in heterogeneous media using FEM can be computationally time consuming and expensive [171]. To determine the distribution of stress in heterogeneous media, deep learning is utilized to create a series of unique Difference-based Neural Network (DiNN) frameworks based on engineering and statistical information [171]. Difference-based Neural Network (DiNN) structure is shown in the figure 10 [171].

To predict the mechanical properties of a family of two-phase materials using their microstructural images, supervised machine learning is used. The machine learning modeling framework of the study is shown in the figure 11.

8 Conclusion and Future Research Work Directions

A composite material is made up of two components that have distinct physical and chemical properties. When the materials are mixed, new materials are created which are specialized to perform a specific task, such as becoming stronger, lighter, or more resistant to electricity. To simulate and analyze the mechanical and thermal properties of composite materials such as standard deviation, strength and flexibility, instability, rigidity, fatigue crack propagation, toughness and ability to repudiate creep, advanced nonlinear differential equations are presented. Mathematical procedure can be used in order to create both advanced analytical models of fiber reinforced composite materials. Then, the analytical methods can be applied to the differential equations in order to obtain the exact solutions of the developed equations. Mechanical as well as thermal analysis of complex composite structures can numerically analyzed in order to increase the performances of composite structures in different working conditions. Thermal stress as well as effects of static and dynamic leads to the new designed shapes of composite structures can be analytically investigated to decrease the failure rate and increase performances of composite structures. The numerical solutions can obtain the closed form of exact solution for the generated nonlinear differential equations of thermal and mechanical properties of composites. Then, the obtained exact solutions of the advanced nonlinear differential equations can be used in terms of designing and developing the applications of composites in different industries. Delamination problems of composite materials can be studied by using the mathematical modeling in order to decrease the failure rate in the composite structures. In order to increase the safety level as well as performances of the composite structures in working conditions, crack development in elastic composites can be simulated and analyzed. Numerical simulations of composite materials using FEA have improved in accuracy and efficiency analysis in order to predict and prevent the crack development in elastic composites. As a result, the strength of the elastic composite structures can be enhanced using the FEA analysis of applied complex loading systems in virtual environments.

New generations of the composite materials regarding the applied complex loads can be presented by using the applications of machine learning systems in designing and analyzing the composite structures. Damage analysis of the composite materials can be presented in order to be predicted and decreased. Molecular dynamics simulations can be used to identify conductive characteristics of materials and study heat transfer across solid-solid interfaces in advanced nanocomposite structures in the disciplines of nanocomposites and thin film technologies. The optimal quantity of reinforcement in advanced composite materials can be obtained to provide excellent mechanical and tribological properties. Fabrication of nanocomposites by using the advanced additive manufacturing process can be presented in order to control the composition and optimize the properties of the manufactured composite parts. Continuous carbon fiber composites can be optimized and modified utilizing advanced additive manufacturing to improve the thermal and mechanical characteristics of the composite structures in real-world applications. The designing process of composite structures can be developed regarding the environmental concerns of the materials after using and finishing the working life.

The machining operations of new composite structures such as drilling as well as milling can be simulated in virtual environments in order to increase the accuracy as well as efficacy in machining process of composite materials. Cutting temperature as well as residual stress during machining operations of composite structures can be simulated in virtual environments in order to be decreased. The combination of natural, biodegradable materials and synthetic materials as components of composite structures merits further study since it can increase the strength and stiffness of materials while still being environmentally friendly. The effects of humid conditions over an extended period of time and different temperature on the fiber-reinforced polymer matrix composite can be simulated and investigated in order to enhance the failure strain, resistance to plastic deformation and fracture toughness of composite matrices.

Crushing process of composite materials can be simulated by using the numerical simulation in order to be decreased in terms of strength enhancement of composite structures. Shear and normal stresses in adhesively glued composite material joints can be analysed by using the numerical methods in order to decrease the failure rate in the composite structures. The effect of structural adhesives' Young's modulus and Poisson's ratio on natural frequencies of the adhesively glued composite material joints can be simulated and analysed in terms of stability enhancement of composite structures. As a result, the mechanical as well as thermal properties of composite materials and structures can be modified in order to increase safety as well as reliability of produced parts from composite materials. In terms of prediction and modification of advanced composite materials and constructions, artificial neural networks models can reduce the demand of the amount of the training datasets and the possibility for physically inconsistent outcomes.

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