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A comprehensive review on modeling of nanocomposite materials and structures

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ABSTRACT

In this article, authors are about to present a historical review of the researches procured by various scientists and engineers dealing with the nanocomposite materials and continuous systems manufactured from such materials. Nanocomposites are an advanced type of well-known composite materials which have been reinforced with nanosize reinforcing fibers and/or particles. Such materials can be better suited for the industrial applications of which remarkable improved material properties are needed. In other words, the material properties of nanocomposites are superior to those of macroscale composites due to the enhanced features of materials in the nanoscale. These materials are being more and more employed by designers in the aerospace, mechanics and automotive applications as constituent elements instead of the conventional composite materials. Henceforward, it is of great significance to be aware of the researches conducted in this area by researchers to be able to predict the behaviors of structures consisted of such materials in real working conditions. In what follows, the mechanical analyses performed on different types of nanocomposite structures including carbon nanotube reinforced (CNTR), graphene reinforced (GR), graphene platelet reinforced (GPLR), graphene oxide reinforced (GOR) and multi-scale hybrid (MSH) nanocomposite ones will be reviewed and the most crucial highlights of the proposed scientific activities will be discussed.

1. Introduction

Nowadays, many of the industries are going through the implementation of the nanocomposite materials instead of the conventional types of composites as devices designed to perform the desired task. The reason for this trend can be realized while comparing the mechanical, thermal, electrical and optical features of materials in the nanoscale with those of theirs in the conventional macroscale. Indeed, the properties of materials in the nanoscale differ from those of similar materials in the macroscale. Thus, the primary goal from the invention of composite materials, which is the amplification of an initial matrix with the superior properties of the reinforcing phase, can be better satisfied whenever nanosize reinforcements are selected to be employed instead of macroscale ones. As a comparative case, the stiffness of carbon nanotube (CNT) can be in the order of TPa depending on its chirality, whereas, carbon fiber (CF) possesses GPa-order stiffness. So, it is natural to see that the scientific society has moved toward implementing for example CNT instead of CF in designing composite materials to enrich a greater stiffness. Due to this trend, many of the researchers allocated their scientific activities to probe the mechanical behaviors of nanocomposite structures once the structure is subjected to various types of external loadings. However, it must be clarified that the issue of investigation of nanocomposite structures is a completely different problem from analysis of nanosize structures such as nanobeams, nanoplates, and nanoshells. The volunteer readers are advised to read complementary references dealing with the mechanical analysis of nanostructures to earn data about the aforementioned issue [1-6]. In addition, it is worth mentioning that there are lots of nanofillers and nanoparticles which can be employed to improve the material properties of nanocomposites. It is common to use carbon-based nanofillers in an initial resin to improve the material properties of it. In recent years, graphene, graphene oxide (GO) and graphene platelet (GPL) were highly utilized by researchers to reinforce nanocomposite materials. Also, in a recently invented type of nanocomposites, two-scale reinforcing elements will be used to strengthen a desired initial matrix. Actually, in such nanocomposites which are called multi-scale hybrid (MSH) nanocomposites, a group of both macroscale and nanoscale fibers/fillers will be dispersed in a media to enrich material properties even better than those obtained from previously developed nanocomposites. In the MSH nanocomposites, it is common to use CF and a nanosize reinforcing phase together. Furthermore, it is also common to design the desired distribution for the nanosize reinforcement

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across the thickness of the nanocomposite media except for the uniform-type distribution for the goal of reaching enhanced material properties either in the middle or at the upper and lower edges of the analyzed structure. in this type of nanocomposite materials, because of the dependency between the thickness and existence of nanofillers, the obtained nanocomposite is usually called as functionally graded (FG) nanocomposites. The most famous distributions of FG nanocomposites are FG-O, FG-X and FG-A type nanocomposites. The aforementioned names are originated from the cross view of the nanofillers inserted in the primary matrix across the thickness. For instance, in the FG-O nanocomposite structures, the greatest volume fraction of nanoparticles happens at the middle-surface of the structure and the lowest volume fraction is observed at the top and bottom surfaces. Henceforward, the distribution of nanofillers across the thickness seems to be as same as English “O” letter. Via similar procedure, the meaning of the other names assigned to other types of FG nanocomposites can be understood.

In the following steps, we will discuss the numerical and analytical investigations dealing with the constitutive behavior and mechanical responses of CNT reinforced (CNTR) nanocomposites, graphene reinforced (GR) nanocomposites, graphene platelet reinforced (GPLR) nanocomposites, graphene oxide reinforced (GOR) nanocomposites and MSH nanocomposites.

2. CNTR nanocomposites

CNTR nanocomposites are the first kind of nanocomposite which attracted the researchers’ attention toward themselves. In recent years, many articles were published in high-quality international journals and conferences about the mechanical performance of CNTR nanocomposite structures under different static and dynamic excitations. In one of the initial researches about the CNTR nanocomposites, Shi, Feng, Huang, Hwang, Gao [7] presented an investigation about the constitutive equations of such nanocomposite materials with respect to the effects of the aggregation of the nanofillers as well as their inherent wavy nature. In this paper, two crucial issues which occur in the real world were considered and the elasticity tensor of CNTR nanocomposites was calculated regarding these issues. Indeed, CNTs will have a sinusoidal wavy shape because of their big slenderness ration (i. e. large length-to-radius ratio) and this reality was considered in this paper by the development of a novel continuum mechanics based strategy. In addition to the effects of waviness, the influences of CNTs’ agglomeration, which happens because of the great surface to volume ratio of the nanosize fillers, were included in this research. In another research about the CNTR nanocomposite structures, Ke, Yang, Kitipornchai [8] used a finite element (FE) based formulation for the purpose of investigating the natural frequency behaviors of beams consisted of such nanocomposites. In this paper, the obtained governing equations were solved by the means of the well-known Ritz method regarding the influences of nonlinear strain-displacement relations in the framework of the Timoshenko beam hypothesis. Besides, the effects of three types of boundary conditions including simply supported-simply supported (S-S), clamped-clamped (C-C) and clamped-simply supported (C-S) ones were covered in the research procured by Ke, Yang, Kitipornchai [8]. The issue of thermally influences stability problem of FG nanocomposite plates and shells reinforced with CNTs was solved by researchers [9, 10]. In the above researches, the effects of geometrical nonlinearity were included on the basis of the well-known third-order shear deformation theory (TSDT). A similar analysis was performed by Shen, Xiang [11] to probe the vibrational responses of CNTR nanocomposite shells with respect to the effects of nonlinear von-Karman relations. Again, the effects of various types of distributions of nanofillers were covered in this study. In this study, the impacts of shear deformation were considered up to third-order. Moreover, the Eshelby-Mori-Tanaka micromechanical homogenization scheme was utilized by Sobhani Aragh, Nasrollah Barati, Hedayati [12] to consider for the effects of nanofillers’ agglomeration as well as the aligned or straight being of the CNTs on the natural frequency of FG-CNTR nanocomposite panels. They could solve the vibration problem via the well-known generalized differential quadrature method (GDQM) as a powerful numerical method. In another analysis, the temperature-dependency of the CNTs’ material properties was considered by Wang, Shen [13] while analyzing the vibrational characteristics of FG-CNTR nanocomposite rectangular plates rested on an elastic medium in the framework of the TSDT of plates and in the presence of thermal loading to present a reliable thermal analysis. The GDQM was implemented by Yas, Samadi [14] probing both static buckling and dynamic frequency analyses of CNTR nanocomposite beams in the framework of the Timoshenko beam theorem with respect to the effects of various types of nanofillers’ distribution across the thickness of the beam-type element. Combination of the enhanced properties of CNTR nanocomposites with the smart features of piezoelectric materials was procured by Alibeigloo [15], [16] in the framework of an elasticity-type methodology for the static analyses of CNTR nanocomposite plates and panels with smart piezoelectric controllers. Besides, a thermal static stress analysis was presented by Alibeigloo, Liew [17] to determine the stress diagrams of FG-CNTR nanocomposite plates within the framework of the elasticity theorem. In this paper, the governing equations of the problem were solved via an analytical solution for the S-S beams. Ke, Yang, Kitipornchai [18] surveyed the stability problem of FG-CNTR nanocomposite beams in the presence of the effects of inertia. The results of this article can be useful for the dynamic stability analysis of nanocomposite structures. in this paper, the coupled governing equations of the problem were solved by the means of the DQM. In another paper, an FE based kp-Ritz method was employed by Lei, Liew, Yu [19] for the goal of analyzing the free vibration responses of FG-CNTR nanocomposite plates. In this work, two micromechanical homogenization methods were utilized to enrich the equivalent material properties of the nanocomposite. The first one is the extended form of the well-known rule of the mixture and the second one is the Eshelby-Mori-Tanaka approach which is able to consider for the agglomeration of the nanofillers. Besides, up to the first-order, the influences of shear deflection were considered in this paper. Malekzadeh, Shojaee [20] probed the stability problem of quadrilateral plates consisted of some CNTR nanocomposite layers while the influences of shear deformation are included in the framework of the FSDT of plates. They considered the edges of the analyzed plate to be either simply supported or clamped. The effective material properties of the CNTR nanocomposite were obtained utilizing the rule of the mixture with coefficients derived from the molecular dynamic (MD) simulations. Rafiee, Yang, Kitipornchai [21] studied the large amplitude oscillation problem of three-layered smart beams consisted of an FG-CNTR nanocomposite core surrounded by two upper and lower smart piezoelectric facesheets. The influences of the shear deformation are excluded in this research. Following the previous paper, the bifurcation-type buckling problem of smart nanocomposite beams was solved by Rafiee, Yang, Kitipornchai [22]. In this research, the von-Karman relations were extended for Euler-Bernoulli beams while the structure is assumed to be made from a CNTR nanocomposite material with two piezoelectric facesheets. Utilizing a higher-order beam hypothesis incorporated with the nonlinear strain-displacement relations of von-Karman, a giant nonlinear large amplitude static and dynamic analysis was performed by Shen, Xiang [23] on the bending, vibration and buckling problems of CNTR nanocomposite beams. This study was conducted in the presence of the thermal gradients. The issue of thermo-elastic postbuckling analysis of CNTR nanocomposite shells was solved by Shen, Xiang [24] in the framework of a perturbation-based approach whenever the shell is assumed to be subjected to axial and radial excitations. The influences of shear deformation were included in this analysis, too. Yas, Pourasghar, Kamarian, Heshmati [25] utilized the GDQM solution for the free vibration analysis of nanocomposite shells reinforced with CNTs on the basis of the theory of elasticity and 3D analysis. In another research in this area, 3D elasticity solution of CNTR nanocomposite cylindrical shells covered by piezoelectric layers was presented by Alibeigloo [26] on the basis of Fourier expansions. On the other hand, the effects of neutral surface and von-Karman type nonlinearity were included in an analysis procured by Ansari, Faghih Shojaei, Mohammadi, Gholami, Sadeghi [27] dealing with the forced vibration problem of CNTR nanocomposite beams with respect to various distributions of CNTs across the thickness of the structure. The effect of first-order shear deflection was included in this research, too. Later, the efficient numerical DQM was used by Heydarpour, Aghdam, Malekzadeh [28] studying the natural frequency behaviors of conical shells fabricated from nanocomposite materials strengthened with CNTs. In this study, the kinematic relations of the FSDT were utilized to obtain the governing equations of the problem. The issue of finding the critical buckling load of CNTR nanocomposite panels was solved by Lei, Zhang, Liew, Yu [29] with the aid of FE formulations. The employed FE method (FEM) is able to solve the problem without separating the structure to a large number of elements and due to this reason, it is named the element-free kp-Ritz method. It is worth mentioning that in many papers the static and dynamic behaviors of CNTR nanocomposite structures were surveyed whenever the continuous system is assumed to be subjected to different types of mechanical and thermal loadings. In these researches, several beam, plate and shell theories were employed either to include or to exclude the effects of shear deformation in the mechanical analysis of nanocomposite structure. It is also interesting to point out that these problems were solved via both analytical and numerical solution methods. Herein, it is avoided to discuss all of these papers and readers are deeply advised to see Refs. [30-57].

As stated before, consideration of the effects of the CNTs' agglomeration on the mechanical responses of CNTR nanocomposite structures is of incredible importance because in the real world this phenomenon happens and some of the nanofillers will be involved in the van der Waals (vdW) potential of the others and a non-uniform distribution of the NTs can be seen which is not admirable at all. Henceforward, some of the researchers tried to consider this issue in their analyses on the mechanical behaviors of CNTR nanocomposite beams, plates, and shells. In one of the most significant articles in this area, Tornabene, Fantuzzi, Bacciocchi, Viola [58] developed the well-known Carrera Unified Formulation (CUF) for a higher-order shear deformation shell theory with dual curvature to enrich the governing equations of the vibration problem of CNTR nanocomposite doubly-curved shells with respect to the effects of CNTs' agglomeration. The aggregation phenomenon was modeled via a graded distribution for the volume fraction of the nanofillers across the thickness of the shell. Coupling the influences of geometrical nonlinearity with geometrical imperfection for the Timoshenko beam hypothesis, Wu, Yang, Kitipornchai [59] probed the vibrational characteristics of FG-CNTR nanocomposites implementing the so-called Ritz method as a powerful FEM. The postbuckling problem of FG-CNTR nanocomposite shear deformable plates was solved by Zhang, Liew, Reddy [60], [61] with respect to the influences of both axial and biaxial type compressions. Application of piezoelectric patches on the controlling the mode shapes of the fluctuations of a CNTR nanocomposite plate was shown by Zhang, Song, Liew [62] according to the TSDT of Reddy. The piezoelectric actuators and sensors are placed at the top and bottom surfaces of the plate, respectively. On the other hand, Ansari, Torabi, Faghih Shojaei [63] investigated the buckling and vibration problems of CNTR nanocomposite sector plates using the variational DQM (VDQM) for sector plates with various boundary conditions (BCs). The discrete singular convolution method (DSCM) was implemented by Civalek [64] to analyze the vibrational behaviors of FG-CNTR nanocomposite shells and plates using the governing equations obtained from the FSDT. The thermally affected dynamic behaviors of beams and plates consisted of FG-CNTR nanocomposite layers were explored by Ebrahimi and his cooperators [65, 66] on the basis of higher-order shear deformation beam and plate hypotheses. In another endeavor, an isogeometric analysis (IGA) was conducted by Fantuzzi, Tornabene, Bacciocchi, Dimitri [67] to study the free vibration problem of FG-CNTR nanocomposite plates with arbitrary shapes regarding for the effects of the aggregation of the nanosize reinforcements. They derived the motion equations of the plate ion the basis of the FSDT. A numerical investigation was procured by García-Macías, Rodríguez-Tembleque, Castro-Triguero, Sáez [68] to consider for the postbuckling problem of FG-CNTR nanocomposite panels while the structure is subjected to axial compression. This study includes the effects of the nanofillers' aggregation as well as the aligned or straight insertion of the NTs in the matrix. Ghorbani Shenas, Malekzadeh, Ziaee [69] utilized the FE based Ritz method with Chebyshev shape functions to solve the vibration problem of FG-CNTR nanocomposite beams in the presence of the thermal loading. In this article, the influences of the pre-twisting phenomenon which happens in the long CNTs were considered to depict more reliable results. In addition, implementation of the layer-wise composite analysis for the static and dynamic problems of CNTR nanocomposite plates was procured by Kumar, Srinivas [70] in the framework of higher-order shear deformable plate theories. Nejati, Asanjarani, Dimitri, Tornabene [71] utilized the GDQM to enrich the natural frequency of FG-CNTR nanocomposite conical shells on the basis of higher-order shear deformation shell theories. Putting emphasis on the influence of arbitrary BCs on the variation of the natural frequency of FG-CNTR nanocomposite beams, Shi, Yao, Pang, Wang [72] solved the free vibration problem of the aforementioned structure implementing the Ritz method. In a similar article, the effects of BCs on the dynamic behaviors of FG-CNTR nanocomposite shallow shells were included in an investigation performed by Wang, Cui, Qin, Liang [73]. In this article, the shell was modeled via the FSDT to account for the effect of shear deflection up to first-order. The Ritz-variational energy method was utilized by Wang, Qin, Shi, Liang [74] to study the free vibration problem of FG-CNTR nanocomposite axisymmetric shells and panels with respect to various types of BCs. Zarei, Fallah, Bisadi, Daneshmehr, Minak [75] presented a numerical study dealing with the thermally affected impact responses of FG-CNTR nanocomposite plates considering the influences of various BCs on the basis of the meshless Ritz method. In this analysis, the influence of temperature on the impact responses of the nanocomposite structure was considered, in particular for reference temperatures of 300, 500 and 700 Kelvin degrees. The TSDT of Reddy was implemented by Zhang, Song, Qiao, Liew [76] to analyze the dynamic responses of FG-CNTR nanocomposite cylinders in the presence of the effect of an impactor. In this study, the shell was assumed to be S-S and the motion equations were solved easily on the basis of the well-known Navier's method. Ebrahimi, Farazmandnia [77] solved the stability problem of the CNTR nanocomposite multi-layered beams with respect to the impacts of the thermal environment on the critical buckling load of the beam. In another research project, the wave dispersion problem of CNTR nanocomposite beams and plates was solved by Ebrahimi, Rostami [78], [79] by the means of an efficient exponential analytical solution method. Wang, Pang, Qin, Liang [80] used the FSDT to solve the natural vibration problem of FG-CNTR nanocomposite shells and panels in the framework of an axisymmetric study regarding for general BCs by connecting the nanocomposite structures to a set of springs. Zghal, Frikha, Dammak [81] surveyed the nonlinear bending problem of FG-CNTR nanocomposite doubly-curved shells using the FE formulations. In this research, the shear deformation effects were included up to third-order obtaining the TSDT of Reddy. Another attempt was conducted by Zhong, Wang, Tang, Shuai, Qin [82] to present a numerical solution to determine the natural frequency of FG-CNTR nanocomposite circular and annular complete or sector plates based upon the well-known FSDT of plates in the polar coordinate system. On the other hand, the constitutive behaviors of CNTR nanocomposite materials were investigated by Zhu, Jeong, Lim, Yun [83] considering the effects of CNTs' waviness and their orientation in the media. This simulation was performed on the basis of a probabilistic multi-scale modeling process. Moreover, a thermo-mechanical buckling study was carried out by Ebrahimi, Hajilak, Habibi, Safarpour [84] about the CNTR nanocomposite shells with respect to the influences of the viscose fluid flow in the shell. In this paper, the nanocomposite structure is considered to be rotating around its axial axis. Lately, the effect of the interface between nanofillers and matrix was included in a Mori-Tanaka based investigation about the constitutive equations of CNTR nanocomposites containing wavy CNTs.

3. GR nanocomposites

Another type of nanocomposite materials which is a perfect alternative for engineering applications is certainly GR nanocomposites. As same as CNTR nanocomposites, this type of nanocomposite materials can be enriched inserting graphene in an initial matrix to strengthen the material to be used in particular applications. Many papers can be found dealing with the analysis of continuous systems consisted of GR nanocomposites. For instance, Mirzaei, Kiani [85] implemented the NURBS mathematical approximation to procure an IGA about the thermo-mechanical buckling problem of FG-GR nanocomposite plates using the FSDT of plates to consider for the shear deformation up to first-order. A nonlinear investigation is carried out by Shen, Lin, Xiang [86] to probe the thermal vibration behaviors of FG-GR nanocomposite beams while the nanocomposite structure is assumed to be rested on an elastic substrate. In this study, the kinematic relations of the beam-type element were achieved on the basis of the Reddy's TSDT and the achieved equations were solved by the means of a two-step perturbation technique. Moreover, the thermal stability and bending analyses of GR nanocomposite beams were investigated by Shen, Lin, Xiang [87] in the framework of the nonlinear expansion of higher-order shear approximation beam theories. As same as former article proposed by these authors, herein a two-step perturbation scheme was employed for the purpose of solving the obtained nonlinear governing equations. Shen, Xiang, Fan [88] probed the nonlinear vibrating responses of GR nanocomposite shells on the basis of higher-order shell theories. The influences of subjecting the shell to a thermal environment were included in the aforementioned paper, too. In addition, the issue of thermally affected buckling and postbuckling of FG-GR nanocomposite plates was investigated by Shen, Xiang, Lin [89] with respect to the temperature-dependent being of the material properties of the graphene. In this article, the plate was modeled via a higher-order kinematic plate hypothesis and it is considered to be rested on an elastic medium. In another paper, the same authors showed the nonlinear deflection behaviors of FG-GR nanocomposite plates whenever the plate is embedded on an elastic foundation [90]. The influences of nonlinear strain-displacement relationship on the thermo-elastic natural frequency and buckling load behaviors of FG-GR nanocomposite plates were probed by Shen, Xiang, Lin [91] and Shen, Xiang, Lin, Hui [92], respectively while the studied structure is assumed to be rested on an elastic substrate. The issue of low-velocity impact responses of GR nanocomposites ws studied by some of the researchers on the basis of higher-order shear deformation kinematic hypotheses [93, 94]. In these papers, the beam- and plate-type structures were assumed to be fabricated from multi-layered GR nanocomposites and embedded on a viscoelastic substrate to control the dynamic responses of the continuous system while attacked by an impactor. García-Macías, Rodriguez-Tembleque, Sáez [95] carried out an FE study about the bending behaviors and natural frequency characteristics of nanocomposite plates reinforced via both graphene and CNT. The employed micromechanical homogenization procedure is powerful enough to estimate the influences of CNTs' agglomeration on the mechanical responses of the plate. Besides, the governing equations were achieved according to an expansion of the FSDT for plates. Kiani [96] explored the large amplitude natural frequency behaviors of FG-GR nanocomposite higher-order plates in the presence of thermal loading within the framework of a NURBS-based IGA. The postbuckling characteristics of FG-GR nanocomposite beams and plates were investigated on the basis of first- and third-order kinematic theories of beams and plates, respectively [97, 98]. Lei, Su, Zeng, Zhang, Yu [99] utilized the kp-Ritz numerical solution for the thermal stability analysis of FG-GR nanocomposite multi-layered plates according to the FSDT. In another project, the influences of axial compression, thermal loading and external pressure on the critical postbuckling responses of cylindrical shells and panels manufactured from FG-GR nanocomposite materials were included in separate articles developed by researchers [100-102]. Besides, the nonlinear von-Karman relations were expanded by Shen, Xiang, Fan, Hui [103], [104] to analyze the bending and vibration behaviors of FG-GR nanocomposite panels with respect to the effects of thermal environment on the mechanical response of the continuous system. The motion equations were derived according to the displacement field of the TSDT of Reddy. On the other hand, Fan, Xiang, Shen [105] procured a forced vibration analysis on the FG-GR nanocomposite shear deformable plates whenever the plate is presumed to be embedded on a viscoPasternak substrate. In this article, the von-

Karman type geometrical nonlinearity was considered to present more reliable results. In the newest research in this field, the thermal buckling analysis of FG-GR nanocomposite conical shells was performed by Kiani [106] implementing an FE solution in association with the FSDT.

4. GPLR nanocomposites

Another derivative of carbon which is used in the nanocomposites in recent years is GPL. Such nanostructures possess Young's moduli of TPa order as same as graphene itself or CNT. It is reported that as well as the improved mechanical properties of GPLR nanocomposites, such materials can reveal superior thermal and electrical features [107]. Kitipornchai, Chen, Yang [108] reported the vibrational responses of FG-GPLR nanocomposite beams on the basis of the FSDT of beams incorporated with the Ritz method with respect to the influences of the existence of porosities in the nanocomposite media. Both free and forced vibration responses of FG-GPLR nanocomposite plates were analyzed by Song, Kitipornchai, Yang [109] according to the kinematic relations of the FSDT of rectangular plates. The governing equations were solved for the simply supported BCs within the framework of the well-known Navier-type solution. The nonlinear buckling and postbuckling characteristics of FG-GPLR multi-layered nanocomposite plates were probed by Song, Yang, Kitipornchai, Zhu [110] utilizing the perturbation technique. In this paper, the influence of the initial imperfection was considered, too. In another paper, the thermally influenced stability analysis of FG-GPLR nanocomposite plates was carried out by Wu, Kitipornchai, Yang [111] implementing the efficient DQ numerical discretization method. Wu, Yang, Kitipornchai [112] surveyed the dynamic buckling responses of FG-GPLR nanocomposite beams using the strain-displacement relations of the FSDT. The influence of subjecting the nanocomposite to thermal loading is considered, too; also, the governing equations were solved numerically employing the well-known DQM. The static deflection and stress analyses of FG-GPLR nanocomposite beams were performed by Feng, Kitipornchai, Yang [113] on the basis of the nonlinear relations of von-Karman in association with the FSDT. The obtained equations were solved by the means of the FE-based Ritz method. Yang, Wu, Kitipornchai [114] investigated the buckling and postbuckling responses of FG-GPLR nanocomposite beams on the basis of the FSDT. Besides, the nonlinear vibration analysis of GPLR nanocomposite beams was procured by Feng, Kitipornchai, Yang [115] in the framework of the Ritz method incorporated with the Ritz method to enrich the mechanical responses of C-C, C-S, and S-S beams. Barati, Zenkour [116] combined the von-Karman relations with the displacement field on higher-order beam hypothesis in order to solve the postbuckling problem of FG-GPLR nanocomposite structures. The effect of porosities in the media was included in this study as well as that of the geometrical imperfection. The postbuckling load and natural frequencies of first-order porous GPLR nanocomposite beams were reached by Chen, Yang, Kitipornchai [117] utilizing the numerical Ritz method. The 3D elasticity solution of thermally influenced bending behaviors of GPLR nanocomposite rectangular and circular plates was investigated by researchers by considering the effect of the existence of porosities in the nanocomposite material [118, 119]. The issue of postbuckling analysis of FG-GPLR nanocomposite beams was solved in the framework of an iteration-free analytical method with respect to the geometrical imperfection of the beam by Barati, Zenkour [120]. Implementing the Timoshenko beam hypothesis in association with the constitutive equations of GPLR nanocomposite materials, Bahaadini, Saidi [121] solved the vibrational responses of blades in supersonic airflow. Furthermore, dynamic behaviors of FG-GPLR nanocomposite cylinders were monitored by Barati, Zenkour [122] using the FSDT of shells. In this study, the effect of porous being of the nanocomposite material was included in the analysis extending the Halpin-Tsai micromechanical scheme incorporated with the saturated porous model. Dong, Li, Chen, Yang [123] surveyed the natural frequency characteristics of GPLR porous nanocomposite shells with respect to the effect of the structure's spinning motion around its axial axis. In another paper dealing with the frequency behaviors of spinning nanocomposite shells, the nonlinearity effect was included as well as that of the axial loading in an investigation conducted by Dong, Zhu, Wang, Li, Yang [124] seeking for the natural frequency of GPLR shells. The wave dispersion analysis of cylindrical shells reinforced with GPLs was carried out by Ebrahimi, Habibi, Safarpour [125] considering the effects of thermal environment and porosities on the dispersion curves of nanocomposite shells. The von-Karman relations were employed to derive the natural frequency of classical nanocomposite plates strengthened with GPLs [126]. The nonlinear set of governing equations were solved via DQM for various types of BCs. In another paper, the nonlinear frequency analysis of GPLR nanocomposite rectangular plates was carried out by Gholami, Ansari [127], [128] in the framework of shear deformable plate theories. The static and dynamic behaviors of FG-GPLR nanocomposite quadrilateral non-rectangular plates were investigated by the means of an efficient numerical approach, called IMLS-Ritz method [129, 130]. The governing equations were achieved on the basis of the FSDT of plates. Hosseini, Zhang [131] surveyed the thermo-mechanical transient characteristics of GPLR nanocomposite cylinders extending a new micromechanical scheme. The time-dependent responses of the shell were achieved incorporating the finite difference method with the Newmark method. On the other hand, an IGA-based numerical investigation was procured by Li, Wu, Chen, Cheng, Liu, Gao, Liu [132] for the purpose of reaching the deflection, buckling load and natural frequency behaviors of FG-GPLR nanocomposite plates with metallic matrix based upon both FSDT and TSDT. Li, Wu, Chen, Liu, Yu, Gao [133] studied the damped dynamic behaviors of porous GPLR nanocomposite plates with consideration of the geometrical nonlinearity mixing the displacement field of the Kirchhoff-Love plate hypothesis with the nonlinear von-Karman relations. The natural frequency, dynamic deflection and dynamic buckling load of the aforementioned structure were obtained in this study. Various distributions of GPLs were considered by Liu, Kitipornchai, Chen, Yang [134] while investigating the buckling and vibration responses of FG-GPLR nanocomposite cylindrical shells utilizing 3D elasticity regarding for the effect of the existence of an initial pre-stress in the structure. Moreover, Reddy, Karunasena, Lokuge [135] surveyed the vibrational characteristics of FG-GPLR nanocomposite plates embedded on an elastic substrate according to the FSDT. Song, Yang, Kitipornchai [136] carried out the elastic bending and buckling analyses of GPLR nanocomposite plates with respect to the influence of shear deformation up to first-order. They solved the mentioned problems analytically based on the well-known Navier's method. A higher-order shear approximation hypothesis was implemented by Wang, Chen, Hao, Zhang [137] to solve both bending and vibration problems of GPLR nanocomposite doubly-curved shallow shells. On the other hand, the issue of torsional buckling responses of FG-GPLR nanocomposite shells with cutout was studied by Wang, Feng, Zhao, Lu, Yang [138] using the approximations of the FEM. Also, the buckling problem of FG-GPLR nanocomposite shells with cutout was solved by Wang, Feng, Zhao, Yang [139] based on the FEM. Wu, Yang, Kitipornchai [140] analyzed the dynamic buckling behaviors of FG-GPLR nanocomposite plates using the efficient discretization of the DQM. The motion equations were achieved on the basis of the FSDT. An elasticity-based 3D solution for the bending responses of FG-GPLR nanocomposite elliptical plates was developed by Yang, Mei, Chen, Yu, Yang [141]. The nonlinear stability analysis of GPLR nanocomposite arches was performed by Yang, Yang, Liu, Fu [142] on the basis of the Euler-Bernoulli beam hypothesis in the polar coordinate system. Blooriyan, Ansari, Darvizeh, Gholami, Rouhi [143] probed the postbuckling behaviors of GPLR nanocomposite shells with consideration of the combined effects of axial and lateral excitations within the framework of an analytical solution method. In another paper, the stability and frequency behaviors of GPLR nanocomposite plates were investigated by Gholami, Ansari [144] based on the variational DQM (VDQM) utilizing the nonlinear expansion of higher-order plate theory. Furthermore, an FE-based investigation was arranged by Haboussi, Sankar, Ganapathi [145] seeking for the dynamic buckling load of spherical shells reinforced with GPLs employing higher-order kinematic theories in the presence an external pressure affecting the structure. the damped frequency analysis of FG-GPLR nanocomposite beams rested on a three-parameter viscoPasternak medium was performed by Qaderi, Ebrahimi, Seyfi [146] based on a higher-order beam model. Employing the modified Hertz impact model. The low-velocity impact responses of FG-GPLR nanocomposite plates were studied by Song, Li, Kitipornchai, Bi, Yang [147] mixing the von-Karman relations with the FSDT. Lately, Wang, Ye, Zu [148] surveyed the nonlinear frequency behaviors of porous FG-GPLR metal foam cylinders for simply supported shells according to the classical theory of shells excluding the effects of shear deflection.

5. GOR nanocomposites

In addition to the previously introduced nanoparticles which were used in the fabrication of nanocomposites, GO nanosize reinforcement can amplify the stiffness and yield strength of nanocomposites in a remarkable manner [149]. Henceforward, some of the scientists allocated their research projects to analyze the elastic behaviors of nanocomposites strengthened with GO. Fabrication of hydrogenated carboxylated nitrile-butadiene rubber nanocomposites amplified with GO showed that implementation of a low value of GO to the initial matrix can dramatically enlarge Young's moduli of the obtained material [150]. More and more investigations were procured about the enhancement occurred in the GOR cement- or epoxy-based nanocomposites in the recent years and all of the proposed researches put emphasis on the crucial role of GO on the improvement of the material properties of the primary matrix [151-153]. Even though GOR nanocomposites possess enhanced mechanical features, only a few papers can be found in the nanocomposites' literature dealing with the static or dynamic responses of nanocomposite structures consisted of GOR nanocomposite materials. In one of the recent attempts in this field, the FSDT of beams was employed by Zhang, Li, Wu, Zhang, Wu, Jiang, Chai [154] probing the bending, buckling and vibration behaviors of FG-GOR nanocomposite beams. Lately, the thermally influenced vibration problem of FG-GOR nanocomposite plates was solved by Ebrahimi, Nouraei, Dabbagh [155] based on a higher-order refined plate model. The natural frequencies were achieved for the fully simply supported plates implementing the Navier-type analytical solution.

6. MSH nanocomposites

Superior to the aforementioned types of nanocomposite materials, recently a novel type of nanocomposites has attracted the researchers' attention. In this novel type of nanocomposites, named MSH nanocomposites, macroscale fibers are implemented in association with the nanosize reinforcements. Each of the CNT, graphene, GPL, and GO can be utilized in such nanocomposites as the nanofiller as well as macroscale fibers. The homogenization of such materials is of great importance and this procedure was completed in the early 2000s by Thostenson, Li, Wang, Ren, Chou [156] in the framework of an experimental study. Mareishi, Rafiee, He, Liew [157] probed the bending, buckling and vibration behaviors of MSH smart nanocomposites using the nonlinear strain-displacement relations of Timoshenko beam mode. The nonlinear vibration analysis of smart piezoelectric MSH nanocomposite plates was carried out by Rafiee, Liu, He, Kitipornchai [158] utilizing the FSDT incorporated with the von-Karman relations for rectangular plates. The enriched governing equations were solved implementing the well-known Galerkin's method. In addition, the damped viscoelastic dynamic analysis of MSH nanocomposite beams was performed by He, Rafiee, Mareishi, Liew [159]. Rafiee, Nitzsche, Labrosse [160] calculated the natural frequency of rotary MSH nanocomposite beams with arbitrary cross-section shape. Moreover, Ebrahimi, Habibi [161] investigated the thermo-mechanical low-velocity impact behaviors of MSH nanocomposite plates using the TSDT of Reddy incorporated with the von-Karman relations. On the basis of the classical beam theory, Rafiee, Nitzsche, Labrosse [162] probed the nonlinear mechanical responses of MSH nanocomposite beams reinforced with GPLs as the nanosize reinforcing element. Micromechanical studies were carried out by researchers dealing with the constitutive equations of MSH nanocomposite materials with respect to the inherent wavy nature of long and slender CNTs in the presence of the agglomeration of nanofillers [163-165]. Considering the impact of various types of BC on the mechanical deflection of plates, Gholami, Ansari [166] presented a nonlinear bending analysis about the MSH nanocomposite structures by the means of the TSDT. A higher-order shear deformable beam hypothesis was utilized by Ebrahimi, Dabbagh [167] to determine the natural frequency of MSH nanocomposite beams whenever the structure is placed in a thermal environment. The characterization of MSH nanocomposite materials with different types of nanofillers was procured by Rafiee, Nitzsche, Laliberte, Hind, Robitaille, Labrosse [168]. In one of the most recent researches dealing with the mechanical responses of nanocomposite continuous systems, Dabbagh, Rastgoo, Ebrahimi [169] proposed a numerical FE study to obtain the natural frequency of MSH nanocomposite shear deformable beams regarding for the effects of nanofillers' aggregation in the nanocomposite media. Later, the vibrational characteristics of MSH nanocomposite beams reinforced with GO and CF were analyzed by Ebrahimi, Dabbagh [170] using a shear deformable beam hypothesis incorporated with the fundamentals of FE approximations. The TSDT was extended by Karimiasl, Ebrahimi, Akgöz [171] for the doubly-curved shells to survey the stability responses of smart shape memory alloy (SMA) based MSH nanocomposite structures with consideration of the effect of thermal gradient as well as moisture concentration. Besides, the nonlinearity effects were included in a vibration study project to determine both free and forced vibrational characteristics of MSH smart nanocomposite doubly-curved shells [172, 173].

7. Conclusions

Above discussions were proposed to show the remarkable scientific endeavors handled by a wide range of researchers seeking for the mechanical behaviors of nanocomposite materials and structures while effects of various working conditions and realistic phenomena were included. As a brief conclusion, it can be easily found that nearly most of the possible problems which can be defined about CNTR nanocomposites were solved by the authors. The effects of nanofillers' agglomeration and waviness were included in several attempts considering the mechanical responses of such nanocomposites. Also, many publications can be found focusing on the mechanical behaviors of GR and GPLR nanocomposites. However, the behaviors of GOR and MSH nanocomposite materials and structures were not studied a lot and many problems in such fields can be found without any answer. Henceforward, researchers are advised to analyze the mechanical responses of such types of nanocomposites with consideration of the realistic phenomena which happen in the fabrication of nanocomposites like agglomeration of nanoparticles and creation of the interphase zone between the nanoparticle and the initial matrix.

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