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Bending and Buckling Behaviors of Nano/Micro Multiscale Silicon Carbide Fillers-Reinforced Aluminum Composite Plates: A Mixed Numerical Technique

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ABSTRACT

In this paper, a numerical strategy is presented to analyze the bending and buckling responses of aluminum composite plates (ACPs) reinforced by nano-scale silicon carbide and micro-scale discontinuous fiber-like silicon carbide. First, the equivalent mechanical properties of multiscale fillers-reinforced ACPs are predicted using a nested micromechanics-based approach. It is considered that discontinuous fibers are randomly dispersed into the hybrid material system. Thereafter, the finite element (FE) method is employed to evaluate the bending and buckling characteristics of hybrid ACPs. The influences of volume fraction of nano-filler, aspect ratio, alignment and volume fraction of micro-filler, shape and thickness of the plate on the ACP structural responses are examined. The results indicate that reinforcing the metal-based structures by nano/micro multiscale silicon carbide fillers significantly improves their load bearing capacity. The hybrid ACPs with higher volume fractions of multiscale fillers possess larger critical buckling loads. It is observed that by (i) increasing the aspect ratio, and (ii) aligning discontinuous fiber-like silicon carbide, the critical buckling load of ACP is increased, while its maximum deflection is decreased.

INTRODUCTION

Metal matrix composites (MMCs) are widely used in automotive, aircraft and aerospace industries due to their high elastic modulus, great strength, good creep and wear resistance and good thermal properties [1-3]. Aluminum (Al) and it alloys have been frequently considered as the host matrix in fabricating MMCs [4-6]. Also, various materials such as carbon fiber, boron and silicon carbide have been employed as the micron-sized reinforcing phase for MMCs [7-9]. The silicon carbide-reinforced Al matrix composite is one of the most commercial MMCs.

Nowadays, there is an increasing need for silicon carbide/Al MMCs with better physical and mechanical characteristics to meet different requirements in engineering applications. For this reason, research and development studies in the field of MMC construction is continuous. Reinforcing the Al MMCs with nano/micro multiscale fillers is a promising technique among the available approaches to further improve their overall properties [10-12]. For example, Şenel and co-workers [13] made an attempt to synthesize the silicon carbide/Al composite, graphene nanoplatelet (GNP)/Al composite, and silicon carbide/GNP/Al hybrid composite. The ultimate compressive strength of 0.5wt.% GNP-filled Al, and 30wt.% silicon carbide-filled Al composites was increased to 138±4 and 221±6 MPa from 106±4 MPa (for pure Al matrix), respectively. The highest ultimate compression strength was reported for the 0.1wt.% GNP/30wt.% silicon carbide/Al hybrid composites which was measured as 271±7 MPa [13]. Furthermore, the hardness of GNP/silicon carbide/Al MMC was notably higher than GNP/Al and silicon carbide/Al composites. Guo and co-workers [14] found that addition of carbon nanotubes (CNTs) can help to improve mechanical properties and coefficient of thermal expansion (CTE) of silicon carbide/Al MMCs simultaneously. In another study [15], it was demonstrated that addition of multi-walled CNTs along with silicon carbide are advantageous for enhancement in strength and modulus of Al-based composites. Tensile tests were performed by Jain and co-workers [16] to specify the tensile strength, yield strength, and elongation of different types of Al MMCs. The CNT/silicon carbide/Al hybrid composite indicated the maximum tensile strength of 361 MPa, as compared to the

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Al alloy, silicon carbide-reinforced Al, and CNT-reinforced Al composites. The performance of micro-scale silicon carbide and nano-scale silicon carbide complement each other, making the multiscale silicon carbide/Al hybrid composites as the hot topic in the field of advanced structural MMCs. Zhang and co-workers [17] fabricated hybrid Al matrix composites reinforced with micro-scale discontinuous silicon carbide and silicon carbide nanoparticle by squeeze casting. According to tensile tests, it was observed that the tensile strength and elastic modulus of the hybrid MMCs enhance with the increase of the nanoparticle content. Safi and co-workers [18] estimated the effective CTEs of micro/nano multiscale silicon carbide fillers-reinforced Al composites by an analytical micromechanics model. Addition of nano-scale silicon carbide particles decreased the CTE of micro-scale discontinuous silicon carbide/Al hybrid composites.

The structural elements such as beams, plates and shells made of new hybrid composites are commonly subjected to static or dynamic mechanical loadings. Therefore, evaluating their mechanical behaviors for better efficiency purposes and understanding the relation among the structural behaviors and material properties is essential. For example, Rafiee et al. [19] studied large deflections, post-buckling and nonlinear free oscillation of graphene/fiber-reinforced composite beams employing the Euler-Bernoulli beam theory, with a von Kármán-type displacement-strain relation. The influences of content of graphene nanofillers, volume fraction of fibers, and boundary conditions on the structural response were examined. Bakamal and co-workers [20] explored the role of CNT addition in the bending, buckling and vibration behaviors of carbon fabric/polymer hybrid composite plates by a computational method. Presence of CNTs into the hybrid composite structures resulted in a higher natural frequency. Avil et al. [21] studied the effect the multi-walled CNTs on the vibration damping response of unidirectional and bidirectional carbon fiber-reinforced epoxy composites. A literature survey clearly indicates that no study has been performed on the bending and buckling characteristics of nano/micro multiscale silicon carbide fillers-reinforced aluminum composite plates (ACPs). Advanced MMC plates are very important structural components which can be used in numerous fields of engineering applications.

Motivated by the application of hybrid Al-based MMCs in the high-tech industries, an efficient numerical approach is proposed to compute the maximum deflection and critical buckling load of multiscale silicon carbide fillers-reinforced ACPs, in the present study. The equivalent mechanical properties of the hybrid ACPs are predicted in the context of a mixed micromechanical method. The FE model is constructed to address the bending and buckling problems of hybrid ACPs. A detailed parametric study is carried out to explore the effects of different factors, such as volume fraction of reinforcing phases, alignment and aspect ratio of micro-scale filler, plate configuration and its thickness on the bending and buckling characteristics of multiscale silicon carbide fillers-reinforced ACPs. The mixed numerical technique is capable of evaluating the overall mechanical behaviors of metal composite structures containing various types of multiscale fillers.

Theoretical Analysis

In this section, a multistep micromechanical approach is proposed to predict the mechanical properties of nano/micro multiscale silicon carbide fillers-reinforced Al composites first. Then, the bending and buckling responses of a plate made of hybrid Al composite are evaluated using the FE method.

Predicting the mechanical properties of multiscale silicon carbide fillers-reinforced Al composites consists of two steps. In the first step, a micromechanical model is used to determine the elastic properties of silicon carbide nanoparticle/Al nanocomposites. The elastic modulus and shear modulus of particulate nanocomposites are given by [22,23]

$$E_{nc} = \frac{k_s V_f^{0.67} E_m}{1 - V_f^{0.33}(1 - \frac{E_m}{E_f})} + (1 - V_f^{0.67}) E_m \quad (1)$$

$$G_{nc} = \frac{k_s V_f^{0.67} G_m}{1 - V_f^{0.33}(1 - \frac{G_m}{G_f})} + (1 - V_f^{0.67}) G_m \quad (2)$$

in which E_m and G_m are the elastic modulus and shear modulus of matrix, respectively. Also, E_f, G_f and V_f stand for the elastic modulus, shear modulus and volume fraction of reinforcement, respectively. In above equations, k_s refers to the size efficiency factor of nano-filler and this parameter is expressed by the following relation [23]

$$k_s = 1 + \frac{k_0}{\exp\left((\frac{d}{10^{-9}})^a\right)} \quad (3)$$

here, k_0 and a are constants, and d denotes the nanoparticle diameter. In the second step, the FE method is employed to obtain the elastic properties of multiscale fillers/Al composites. A representative volume element (RVE) is constructed in which the discontinuous silicon carbide micro-scale fibers are randomly dispersed in the nanoparticle/Al enriched matrix. It is noted that the enriched matrix properties are equal to the properties of the silicon carbide nanoparticle/Al nanocomposite. The length and diameter of discontinuous fiber are specified by L and D, respectively. The 8-node biquadratic plane stress quadrilateral element is used to mesh the RVE of the discontinuous micro-scale fiber-reinforced composites. Fig. 1 shows the meshed shape of the RVE. Fig. 2 shows the boundary conditions imposed on the RVE. The edge of the RVE in y= 0 is fixed in the y-direction, whereas the opposite edge is free to move, however, must be remained planar to its initial position under loading. Moreover, the edge of the RVE in x= 0 is fixed in the x-direction, whereas the opposite edge is under a specified displacement. The elastic modulus of the hybrid composite can be calculated by the following relation as

$$E_{HC} = \frac{FL}{A\delta} \quad (4)$$

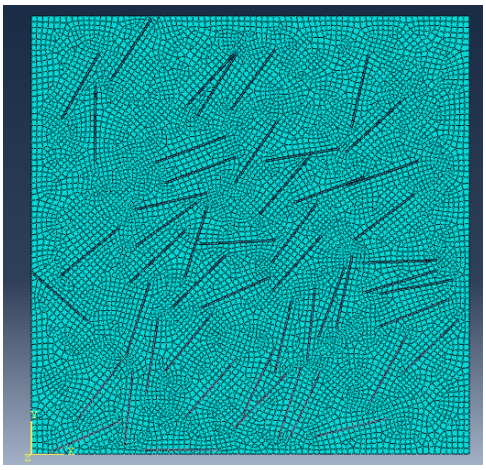


Fig. 1. Meshed shape of the hybrid composite RVE

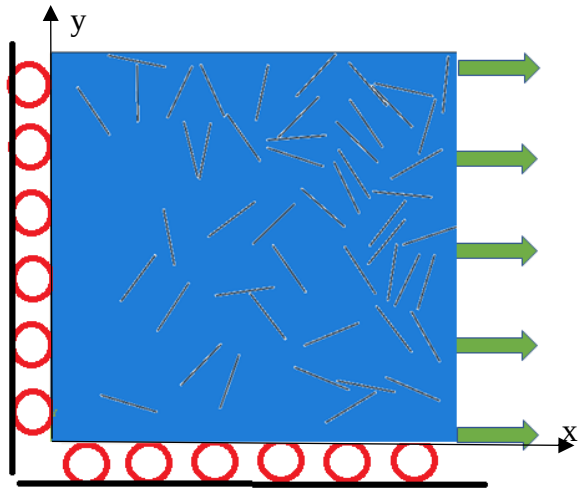


Fig. 2. Boundary conditions on the hybrid composite RVE

where F, L, A, and δ specify the applied force, the edge length among the constrained and loaded surfaces, the cross-sectional area of the constrained surface, and the resultant deformation, respectively. The Poisson's ratio of the hybrid composite RVE can be computed as:

$$v_{HC} = -\frac{\varepsilon_T}{\varepsilon_A} \tag{5}$$

where ε_A and ε_T are the strains along and perpendicular to the loading direction, respectively. The rule of mixture is utilized to determine the density of hybrid composites.

After predicting the mechanical properties of nano/micro multiscale silicon carbide fillers-reinforced Al composites, FE analysis is performed to evaluate the bending and buckling behaviors of hybrid ACPs. Rectangular and circular plates, as well as an annular plate are analyzed in this research, as depicted in Fig. 3. The fully clamped boundary condition is imposed on the plates as shown in Fig. 4. These structures are meshed via 20-node quadratic brick elements at the macro-scale. Fig. 5 shows the meshed shape of the ACPs.

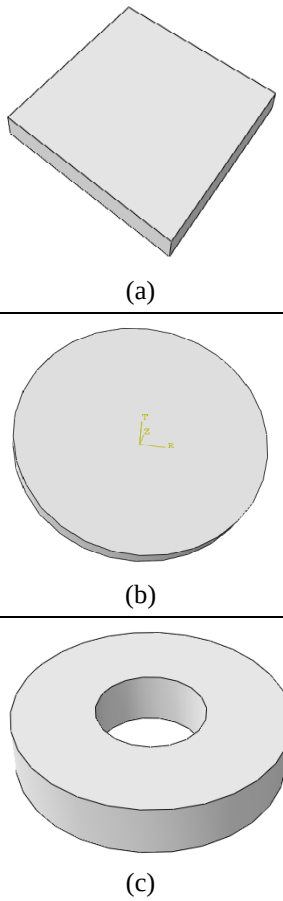


Fig. 3. (a) Rectangular, (b) circular and (c) annular hybrid ACPs

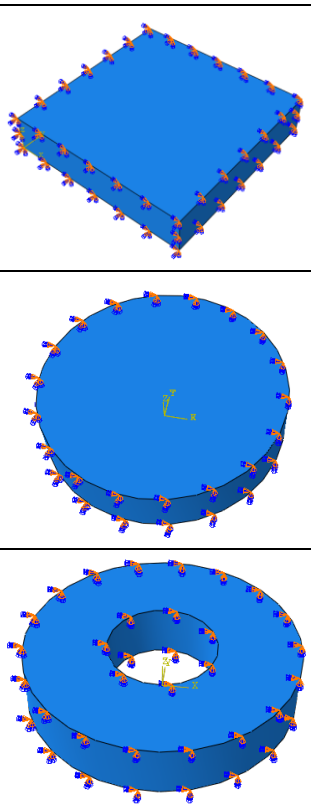


Fig. 4. Boundary conditions of the hybrid ACPs

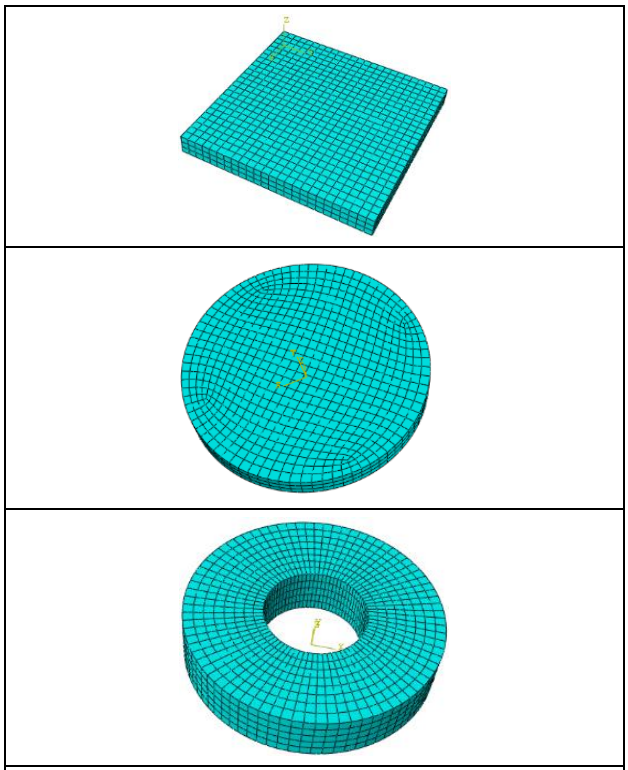


Fig. 5. Meshed shape of the hybrid ACPs

RESULTS AND DISCUSSION

The bending and buckling of clamped hybrid ACPs for various shapes are analyzed using the FE method. The elastic modulus and Poisson's ratio for silicon carbide and Al matrix are 409 GPa, 0.2, and 72.6 GPa, 0.33, respectively. Also, the values of k_0, a and d are considered to be 25, 0.32, and 70 nm [23], respectively. The thickness of all plates equals to 10 mm, and other geometrical parameters are given as: $a = b = 50$ mm (a and b: length and width of rectangular plate), $r = 25$ mm (r: radius of circular plate), and $r_o = 25$ mm, $r_i = 10$ mm (r_o and r_i: outer and inner radii of annular plate). For bending analysis, the plates are assumed to be under a uniformly distributed load with the magnitude of $q = 10^9$ N/m^2.

Table 1
Critical buckling loads (GPa) of ACPs with different shapes

Volume fraction of micro-scale silicon carbide (%)	Volume fraction of nano-scale silicon carbide (%)	Rectangular	Circular	Annular
0	0	5.9973	4.0196	16.571
1	1	6.4186	4.3021	17.741
3	3	6.9818	4.6752	19.295
5	5	7.5960	5.0838	20.991
10	10	9.2428	5.8170	25.297

Table 1 shows the critical buckling load of clamped ACPs for different types of plate shape. The FE results are presented for various values of silicon carbide volume fractions. Multiscale silicon carbide fillers are known to have a substantial effect on the buckling behavior of hybrid composite structures. The higher values of multiscale content lead to greater buckling capacity. It is due to the significant improvement in the mechanical properties of ACPs with increasing the multiscale silicon carbide volume fraction. Fig. 6 shows the buckled hybrid ACPs.

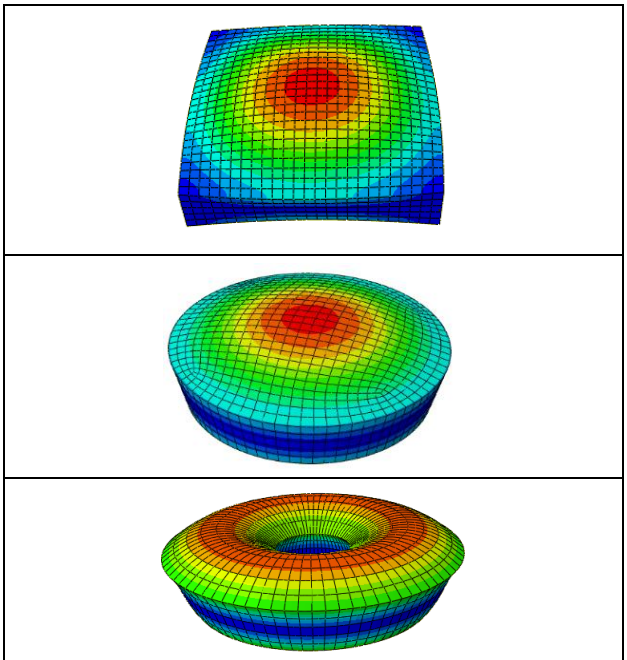


Fig. 6. Buckled hybrid ACPs

The influence of volume fraction of nano/micro multiscale silicon carbide fillers on the deflection behavior of hybrid ACPs is studied. In Table 2, the maximum values of deflection for three types of ACPs are given. As expected, the addition of multiscale fillers has a strong effect on the bending response of plates. The maximum deflection of ACPs decreases as the silicon carbide filler goes higher. The deflected ACPs are graphically presented in Fig. 7.

Table 2
Maximum deflections (mm) of ACPs with different shapes

Volume fraction of micro-scale silicon carbide (%)	Volume fraction of nano-scale silicon carbide (%)	Rectangular	Circular	Annular
0	0	1.982	1.55	0.1648
1	1	1.863	1.447	0.154
3	3	1.709	1.331	0.142
5	5	1.571	1.224	0.1303
10	10	1.318	1.027	0.1285

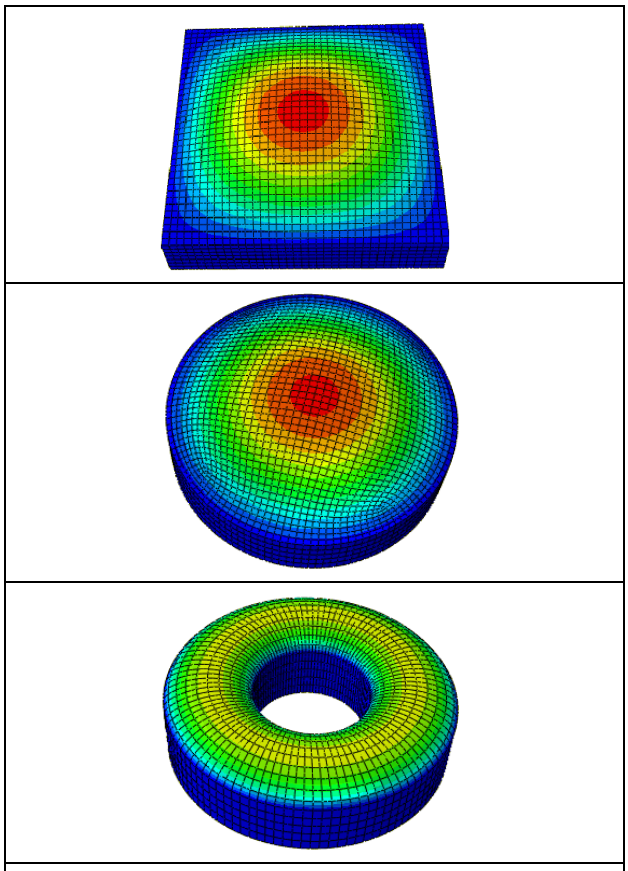
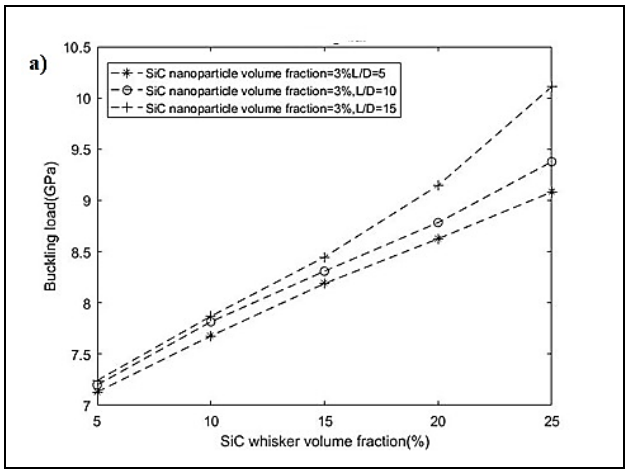


Fig. 7. Deflected hybrid ACPs

The effect of aspect ratio (L/D) of micro-scale discontinuous fiber-like silicon carbide (SiC) on the mechanical behaviors of hybrid ACPs is investigated. Figs. 8-10 show the critical buckling loads of the hybrid ACPs versus micro-scale silicon carbide volume fraction. The numerical results are extracted for three different values of aspect ratio, including 5, 10, and 15. It is found that the buckling behavior of hybrid ACPs can be affected by the microscale filler aspect ratio. The increase of silicon carbide aspect ratio makes the structure more stable, and consequently tends the buckling load to the greater values. It is attributed to the fact that the increase of filler aspect ratio can improve the mechanical properties of hybrid composites.



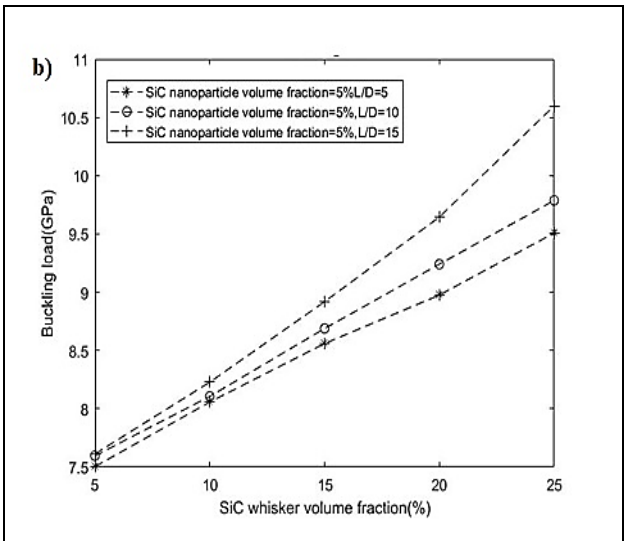


Fig. 8. Effect of aspect ratio of micro-scale silicon carbide on the critical buckling loads of hybrid ACPs with rectangular shape

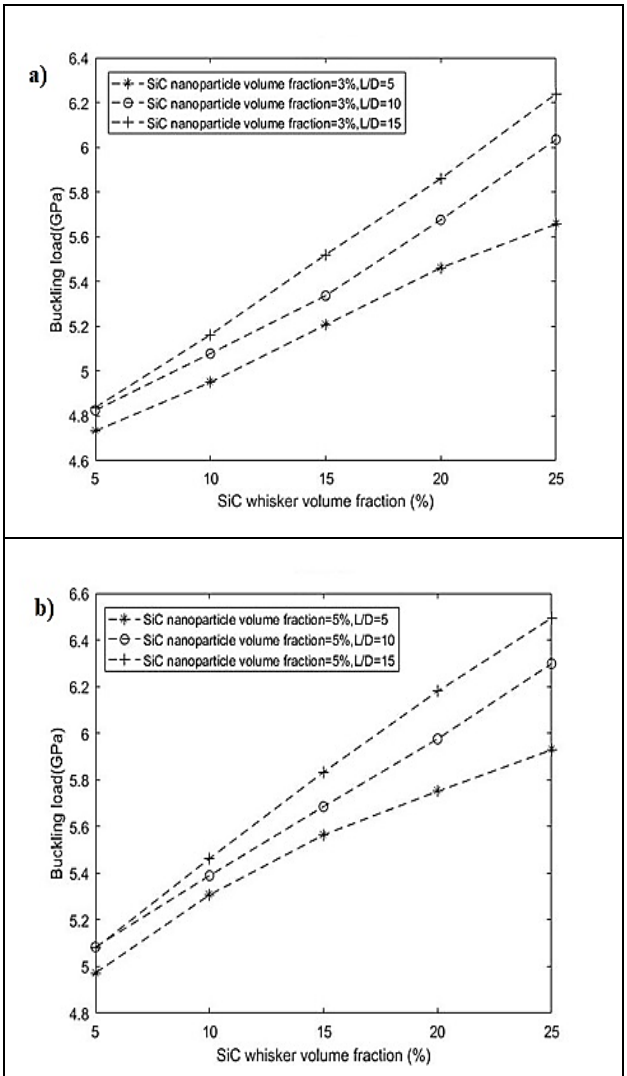


Fig. 9. Effect of aspect ratio of micro-scale silicon carbide on the critical buckling loads of hybrid ACPs with circular shape

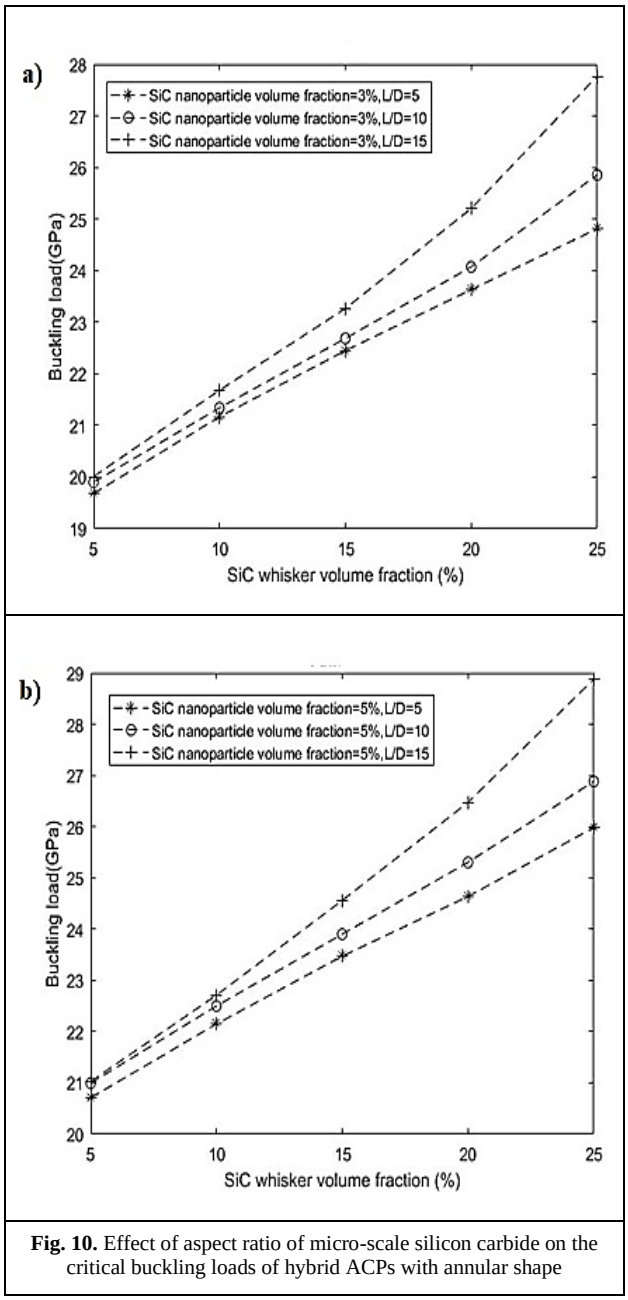


Fig. 10. Effect of aspect ratio of micro-scale silicon carbide on the critical buckling loads of hybrid ACPs with annular shape

Figs. 11-13 indicate the maximum deflections of hybrid ACPs versus microscale silicon carbide volume fraction for different micro-filler aspect ratios. One can see that the silicon carbide aspect ratio has a significant effect on the ACP bending behavior. Due to the enhancement of elastic properties, the maximum deflections of hybrid ACPs with various shapes are decreased by the increase of micro-scale silicon carbide aspect ratio.

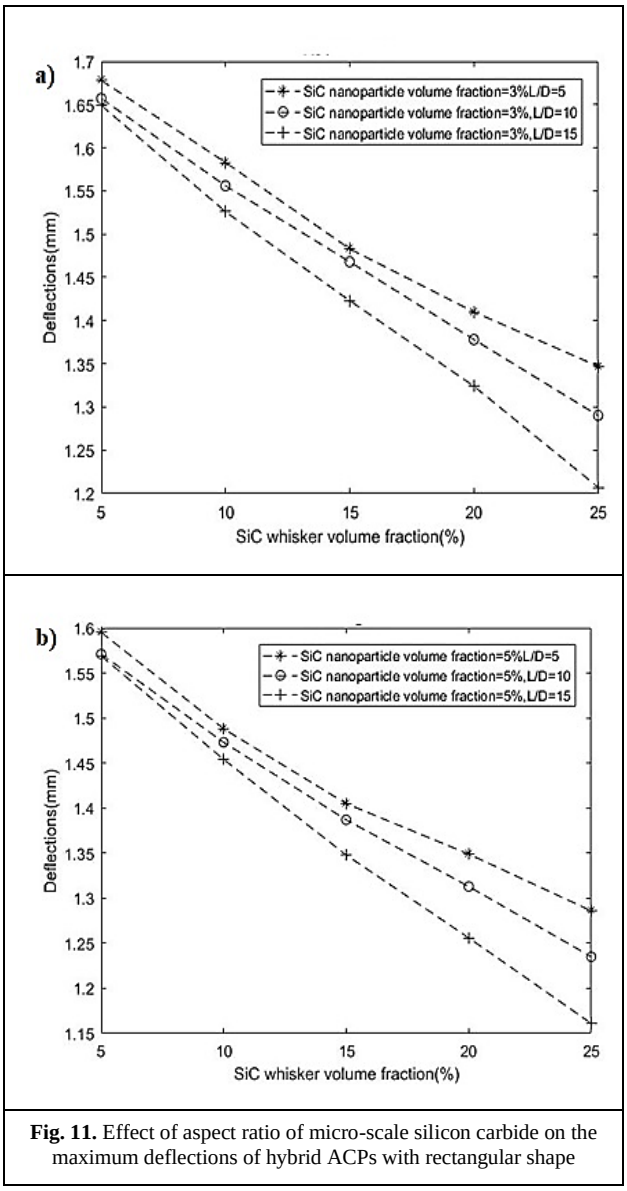
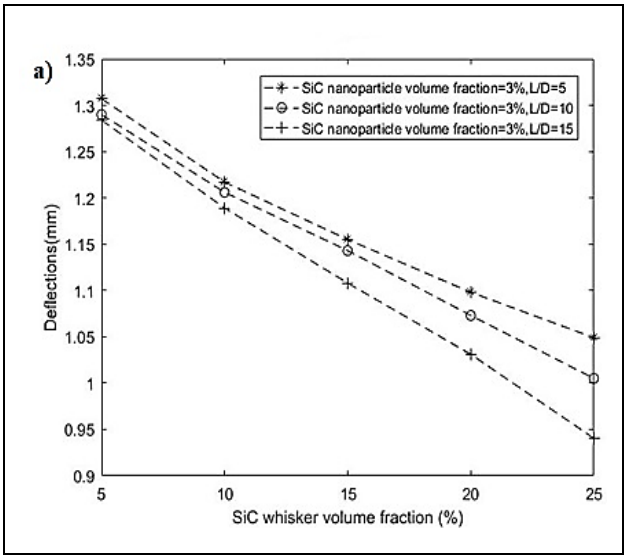


Fig. 11. Effect of aspect ratio of micro-scale silicon carbide on the maximum deflections of hybrid ACPs with rectangular shape



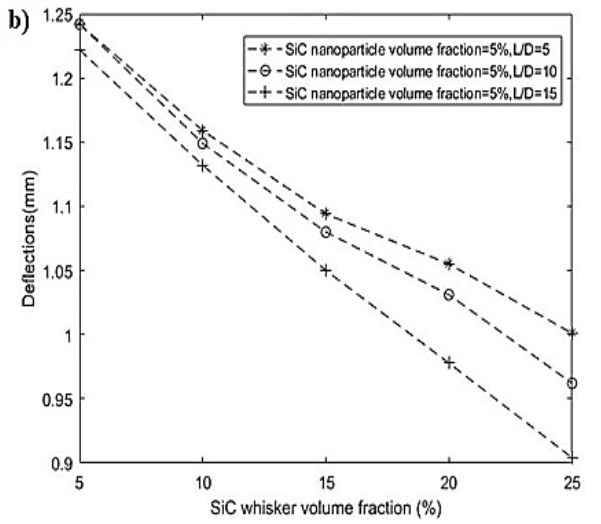


Fig. 12. Effect of aspect ratio of micro-scale silicon carbide on the maximum deflections of hybrid ACPs with circular shape

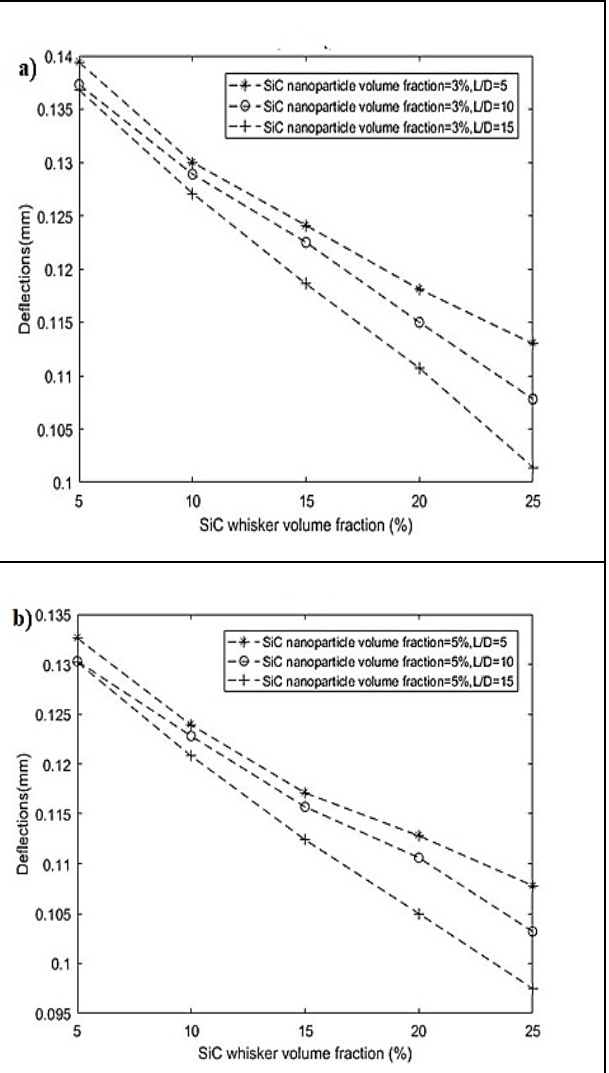


Fig. 13. Effect of aspect ratio of micro-scale silicon carbide on the maximum deflections of hybrid ACPs with annular shape

The proposed method is employed to evaluate the influence of the alignment of micro-scale discontinuous silicon carbide fibers on the mechanical behaviors of hybrid ACPs with rectangular shape. The comparisons between the numerical results with assumption of random dispersion and aligned state are presented in Figs. 14 and 15. It is observed from Fig. 14 that discontinuous fiber alignment leads to the higher value for critical buckling loads. Thus, the alignment of micro-scale silicon carbide fibers provides a considerable improvement of buckling capacity when compared with the random dispersion. Fig. 15 presents result of the bending analysis indicating that aligning the micro-scale silicon carbide fillers results in a lower deflection as compared to the filler random dispersion.

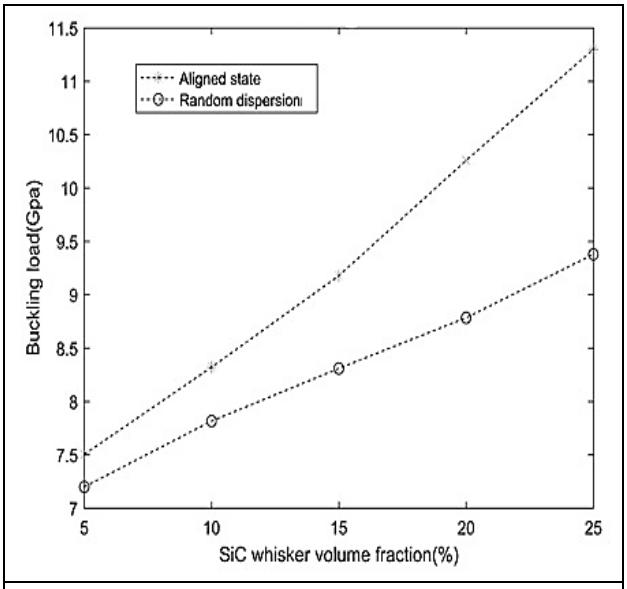


Fig. 14. Effect of alignment of micro-scale silicon carbide on the critical buckling loads of hybrid ACPs with rectangular shape

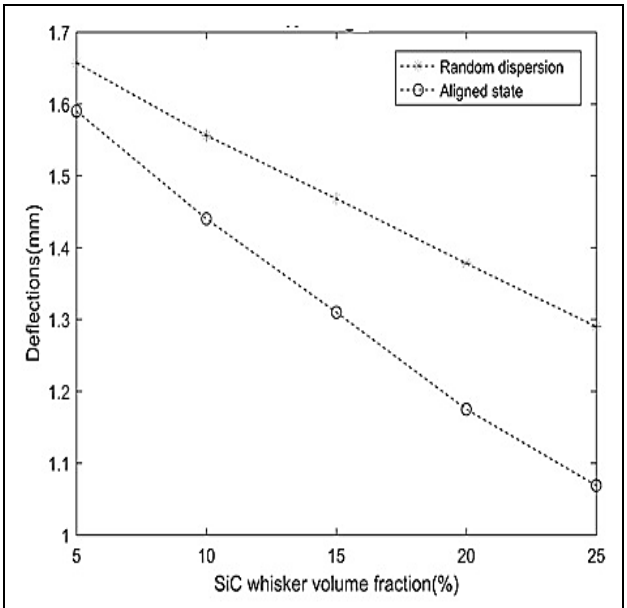


Fig. 15. Effect of alignment of micro-scale silicon carbide on the maximum deflections of hybrid ACPs with rectangular shape

The numerical results of buckling response of hybrid ACPs versus plate thickness are presented in Fig. 16. By the increase of plate thickness, the present model predicts higher values for critical buckling load of the hybrid ACPs. In other words, the buckling capacity of the structure can be increased by the increase of plate thickness. Fig. 17 shows the numerical results of bending response of hybrid ACPs versus plate thickness. It is found that increasing the plate thickness considerably decreases the maximum deflections of the composite structure.

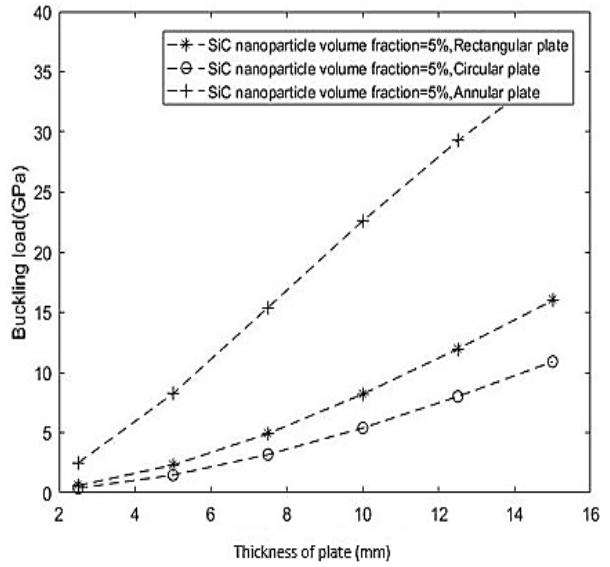


Fig. 16. Critical buckling loads of hybrid ACPs versus plate thickness

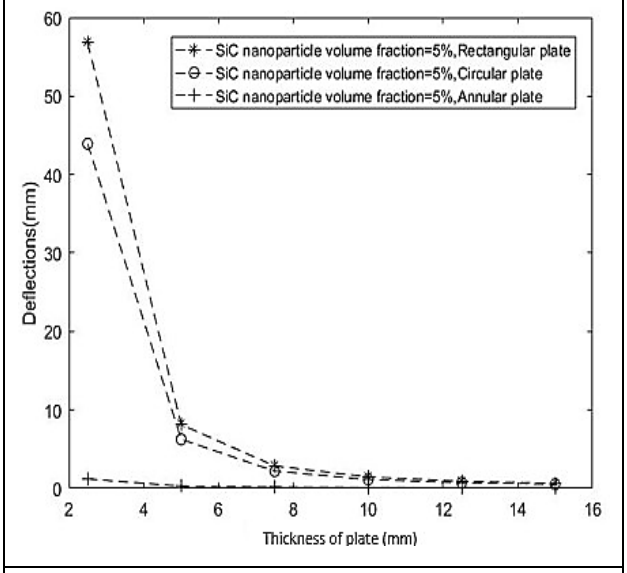


Fig. 17. Maximum deflections of hybrid ACPs versus plate thickness

The convergence of the present numerical method is also investigated. The maximum deflections of the nano/micro multiscale silicon carbide fillers-reinforced ACPs for four different numbers of elements are shown in Table 3.

Table 3
Effect of the number of elements on the maximum deflections (mm) of the hybrid ACPs

Number of elements	Rectangular	Circular
9818	1.647	1.286
14072	1.653	1.289
19522	1.657	1.290
23877	1.657	1.290

CONCLUSIONS

Using a numerical solution strategy, the bending and buckling behaviors of nano/micro multiscale silicon carbide fillers-reinforced ACPs were studied. Rectangular, circular and annular plates with fully clamped boundary conditions were considered. The mechanical properties of the multiscale silicon carbide/Al composites were predicted using a coupled micromechanical model. Then, FE method was used to evaluate the bending and buckling responses of hybrid ACPs. Parametric studies were performed to analyze the effects of volume fractions of multiscale reinforcements, microscale aspect ratio, and plate thickness and its configuration on the ACP mechanical behaviors. It was shown that reinforcing Al matrix by multiscale silicon carbide fillers can increase the critical buckling load and decrease the maximum deflections. Besides, the increase of micro-scale filler aspect ratio resulted in more stable ACPs. The results indicated that alignment of micro-scale discontinuous fillers leads to a significant improvement in the bending and buckling behaviors of the multiscale silicon carbide fillers-reinforced ACPs.

REFERENCES

[1] Chakravarty S, Sikder R, Haldar P, Nandi T, Sutradhar G. Exploring energy aspects and tool wear on dry turning of cupola slag-reinforced aluminium metal matrix composites. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2024 Feb;46(2):59.

[2] Panziera RC, Pereira M, de Medeiros Castro R, Curi EI, Neto FG. Effect of tungsten carbide reinforcement phase on the abrasive wear performance of metal matrix composites deposited by laser cladding. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2023 Nov;45(11):596.

[3] Hayat MD, Singh H, He Z, Cao P. Titanium metal matrix composites: An overview. Composites Part A: Applied Science and Manufacturing. 2019 Jun 1;121:418-38.

[4] Chandla NK, Kant S, Goud MM. Mechanical, tribological and microstructural characterization of stir cast Al-6061 metal/matrix composites—a comprehensive review. Sādhanā. 2021 Dec;46(1):47.

[5] Muralidharan N, Chockalingam K, Dinaharan I, Kalaiselvan K. Microstructure and mechanical behavior of AA2024 aluminum matrix composites reinforced with in situ synthesized ZrB2 particles. Journal of Alloys and Compounds. 2018 Feb 25;735:2167-74.

[6] Maji P, Ghosh SK, Nath RK, Karmakar R. Microstructural, mechanical and wear characteristics of aluminum matrix composites fabricated by friction stir processing. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2020 Apr;42:1-24.

[7] Shirvanimoghaddam K, Hamim SU, Akbari MK, Fakhrhoseini SM, Khayyam H, Pakseresht AH, Ghasali E, Zabet M, Munir KS, Jia S, Davim JP. Carbon fiber reinforced metal matrix composites: Fabrication processes and properties. Composites Part A: Applied Science and Manufacturing. 2017 Jan 1;92:70-96.

[8] Rahman MH, Al Rashed HM. Characterization of silicon carbide reinforced aluminum matrix composites. Procedia Engineering. 2014 Jan 1;90:103-9.

[9] Potti PG, Rao BN, Srivastava VK. Tensile fracture strength of boron/aluminum laminates with holes and slits. Materials Science and Engineering: A. 2001 Mar 31;301(2):244-52.

[10] Muley AV, Aravindan S, Singh IP. Nano and hybrid aluminum based metal matrix composites: an overview. Manufacturing Review. 2015;2:15.

[11] Uzun A. Production of aluminium foams reinforced with silicon carbide and carbon nanotubes prepared by powder metallurgy method. Composites Part B: Engineering. 2019 Sep 1;172:206-17.

[12] Guo B, Chen B, Zhang X, Cen X, Wang X, Song M, Ni S, Yi J, Shen T, Du Y. Exploring the size effects of Al4C3 on the mechanical properties and thermal behaviors of Al-based composites reinforced by SiC and carbon nanotubes. Carbon. 2018 Aug 1;135:224-35.

[13] Şenel MC, Gürbüz M, Koc E. Fabrication and characterization of synergistic Al-SiC-GNPs hybrid composites. Composites Part B: Engineering. 2018 Dec 1;154:1-9.

[14] Guo B, Zhang X, Cen X, Wang X, Song M, Ni S, Yi J, Shen T, Du Y. Ameliorated mechanical and thermal properties of SiC reinforced Al matrix composites through hybridizing carbon nanotubes. Materials Characterization. 2018 Feb 1;136:272-80.

[15] Yadav BN, Verma G, Muchhala D, Kumar R, Mondal DP. Effect of MWCNTs addition on the wear and compressive deformation behavior of LM13-SiC-MWCNTs hybrid composites. Tribology International. 2018 Dec 1;128:21-33.

[16] Jain VK, Yazar KU, Muthukumaran S. Development and characterization of Al5083-CNTs/SiC composites via friction stir processing. Journal of Alloys and Compounds. 2019 Aug 25;798:82-92.

[17] Zhang XN, Geng L, Wang GS. Microstructure and tensile properties of Al hybrid composites reinforced with SiC whiskers and SiC nanoparticles. Key Engineering Materials. 2003 Aug 8;249:277-82.

[18] Safi M, Hassanzadeh-Aghdam MK, Mahmoodi MJ. Effects of nano-sized ceramic particles on the coefficients of thermal expansion of short SiC fiber-aluminum hybrid composites. Journal of Alloys and Compounds. 2019 Sep 30;803:554-64.

[19] Rafiee M, Nitzsche F, Labrosse MR. Modeling and mechanical analysis of multiscale fiber-reinforced graphene composites: Nonlinear bending, thermal post-buckling and large amplitude vibration. International Journal of Non-Linear Mechanics. 2018 Jul 1;103:104-12.

[20] Bakamal A, Ansari R, Hassanzadeh-Aghdam MK. Computational analysis of the effects of carbon nanotubes on the bending, buckling, and vibration characteristics of carbon fabric/polymer hybrid nanocomposite plates. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2021 Feb;43(2):61.

[21] Avil E, Kadioglu F, Kaynak C. Contribution of carbon nanotubes to vibration damping behavior of epoxy

and its carbon fiber composites. Journal of Reinforced Plastics and Composites. 2020 Apr;39(7-8):311-23.

[22] Mital SK, Murthy PL, Goldberg RK. Micromechanics for particulate-reinforced composites. Mechanics Of Composite Materials And Structures An International Journal. 1997 Jul 1;4(3):251-66.

[23] Hassanzadeh-Aghdam MK, Mahmoodi MJ, Ansari R. A comprehensive predicting model for thermomechanical properties of particulate metal matrix nanocomposites. Journal of Alloys and Compounds. 2018 Mar 30;739:164-77.