**On Stasic Stability Behaviors of CFRP Porous Plates: a Micromechanical Investigation Concerning the Influence of the Interphase**

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Abstract

In the present manuscript, the buckling behaviors of carbon fiber reinforced polymer (CFRP) plates will be probed for the first time. The coupled influences of existence of symmetrically and asymmetrically distributed pores in the media and implementation of graphene platelets (GPLs) as the coating of the CFs on the mechanical responses of the system will be covered, too. The GPL coatings will construct a GPLs-reinforced interphase which helps the structure to tolerate greater buckling loads. The effective stiffness of the system will be enriched utilizing a micromechanical procedure regarding for the influence of available porosities in the material. Afterward, the principle of virtual work will be used for the goal of deriving the governing equations of the plate-type structure based upon the expansion of the displacement field of a refined-type higher-order shear deformation theory (HSDT). At the end, the buckling load of the system will be obtained solving the eigenvalue buckling problem within the framework of the Navier’s well-known analytical solution for the case of which all of the edges are simply supported. The validity of the proposed investigation is examined and a mentionable agreement between the results of this work and those available in the open literature is observed. The generated results indicate on the crucial role of the GPLs-reinforced interphase on the stability endurance of the CFRP plate.

Keywords

Buckling analysis, carbon fiber reinforced polymer (CFRP), porosity effects, graphene platelet (GPL) coating, GPLs-reinforced interphase

1. **Introduction**

Carbon fiber reinforced polymers (CFRPs) are one of the most famous categories of the FR composites (FRCs). Such materials can reveal remarkable performance from themselves due to their strengthened material properties. In fact, addition of the CFs to the polymers can reveal a composite which possesses light weigh as well as improved stiffness due to the existence of only a small amount of the CFs in it. The experiments have proven that the mechanical performance of such polymeric composites deeply depends on the length of the fiber [1]. Due to the aforementioned features, CFRPs can be excellent candidates for the goal of being used in the infrastructures in order to strengthen the mechanical endurance of the steel-concrete systems [2]. In another experimental research, the seismic resistance of reinforced concrete (RC) was upgraded using CFRPs within the framework of a retrofitting process [3]. On the other hand, the influence of the fibers’ length on the thermo-mechanical and time-dependent properties of the CFRPs was included in an experimental research carried out by Rezaei *et al.* [4] based upon the results of both dynamic mechanical analysis (DMA) and thermal gravimetric analysis (TGA). It was reported that the mechanical performance of the CFRPs can be enhanced using longer CFs in the composite. It is noteworthy that CF is not the only fiber which is highly used in the FRPs. In other words, some other fibers are mentioned in the literature which can be employed for the goal of reinforcing a polymeric matrix. For instance, glass fibers (GFs) can exhibit exclusive mechanical performance including high strength and light weight from themselves in the cases of which they are used as the reinforcing phase of polymers [5]. As a part of a giant project, the towers of a wind turbine were manufactured from GFRP and the experimental tests certified the applicability of this type of FRPs for the aforementioned device [6].

Because of the significance of the FRP materials and their widespread application in fabrication of the engineering devices, some of the researchers tried to analyze the mechanical responses of such composites. For example, Raftoyiannis and Polyzois [7] experimentally explored the dynamic responses of GFRP tapered poles considering semi-rigid connections instead of fully flexible ones. Later, Khalili and Saboori [8] followed a finite element (FE) procedure in order to track the time-dependent responses of tapered transmission poles fabricated from GFRPs. The same authors [9] could procure static analysis of the aforementioned GFRP device implementing the FE method (FEM). In addition, the vibration frequency of the GFRP tapered poles was calculated by Saboori and Khalili [10] considering the influences of flexible joints. They could reach at acceptable responses in comparison with those obtained via the well-known FE-based commercial software, ANSYS. Another investigation was accomplished by Hemmatnezhad *et al.* [11] concerned with the frequency behaviors of GFRP-stiffened shells. Furthermore, Sharif Zarei *et al.* [12] carried out a nonlinear dynamic analysis dealing with the seismic reaction of the FRP concrete shells once the structure is assumed to be underwater. An experimental static stability analysis was recently performed by Alshurafa *et al.* [13] dealing with the determination of the failure load of a FRP towers.

As stated in the above paragraphs, the mechanical behaviors of FRP composites were explored by many of the researchers in the recent years. Once reviewing the previous paragraphs, one can realize that the influences of the interphase between the fibers and the matrix are not covered a lot. However, this issue is of great importance and must be absolutely considered to enable one to rely on the extracted numerical results. In one of the researches dealing with the influence of the interface on the mechanical behaviors of the system, the effect of implementing carbon nanotube (CNT) coatings on the CFs on the interfacial shear strength of CFRPs was studied by Sager *et al.* [14]. Maligno *et al.* [15] procured a micromechanical study as well as an FE one, dealing with the influence of interphase on the stress-strain and failure initiation behaviors of FRPs. The results of their research indicates that the mechanical behaviors of the system can be tailored changing the stiffness of the interphase zone. Later, the influence of using CNT coatings on the GFs, dispersed in a resin, on the mechanical behaviors of GFRCs was monitored in an experimental manner by Wood *et al.* [16]. Zhang *et al.* [17] observed an increment in the material properties of CFRPs once graphene oxide (GO) were implemented to be in the role of coating for the CFs. On the other hand, a gradient interphase was designed by Chen *et al.* [18] for the purpose of enhancing the mechanical performance of CFRPs using silanized GO coatings. Furthermore, the effect of adding CNT coatings to the fibers of FRCs on the local stress between matrix and interphace was shown by Jin *et al.* [19] using both low and high moduli CFRCs. Also, Qin *et al.* [20] showed that implementation of GPLs as coatings on the fibers can affect electromechanical properties of the enriched composite. They reported increments in both interlaminar shear strength and electrical conductivity of the composite once GPL coatings are utilized. The impacts of using GO and reduced GO (rGO) as coatings in FRCs were included in another paper accomplished by Mahmood *et al.* [21]. It was reported that utilization of the GOs is the best way to improve the stress-strain behaviors of the FRC. In one of the recent researches, CNTs and GPLs were employed to be the coatings of the steel fiber-reinforced polymers in order to approximate the stress concentration characteristics of such composites [22]. Lately, Pawlik *et al.* [23] presented a micromechanical framework for the underestimation of the mechanical properties of the interphase in FRCs once the fibers are coated with GPLs.

As explained in the above literature review, it can be well understood that there exists no accomplished research on the stability behaviors of CFRPs whenever the effects of the interphase between the fibers and the matrix is considered. However, the issue of stability analysis is of great significance in a mechanical engineer’s point of view for the goal of designing composite devices. Motivated by the available lack and the necessity of in-hand reliable data about the stability of structures manufactured from CFRPs, authors found it crucial to procure a stability analysis dealing with the buckling responses of porous CFRPs once the CFs are coated via randomly oriented GPLs to cover the effects of the interphase on the mechanical response of the system. In what follows, the theoretical framework of the problem will be presented in section 2, followed by presenting an analytical solution for the buckling analysis. Afterward, the numerical examples will be depicted in section 4 to show the effects of the involved terms in determination of the mechanical response of the continuous system.

1. **Theoretical Framework**

In this section, the mathematical tools required to formulate the problem will be depicted. The plate-type element is assumed to be manufactured from CFRP while the effects of GPLs-reinforced interphase is considered. The equivalent material properties of the composite will be determined in section 2.1. Afterward, the proper constitutive equation corresponding with the implemented material will be presented in section 2.2. In addition, section 2.3 is allocated to introduce the kinematic fundamentals of the implemented plate hypothesis. Thereafter, the virtual work’s principle will be employed in section 2.4 in order to derive the Euler-Lagrange equations of the plate’s motion. Next, the governing equations of the problem will be enriched in section 2.5. In addition, section 3 is allocated to solve the buckling problem for fully simply supported plates and the results of the proposed work will be presented within the framework of section 4 followed by presenting the most significant highlights in section 5.

* 1. Micromechanical homogenization procedure

In this section, the equivalent material properties will be derived using a micromechanical homogenization scheme. First of all, the material properties of the interphase must be found. To this purpose, we decided to consider the case of having randomly oriented GPLs in the interphase of the CFRP. This case generates more reliable results in comparison with the case of considering aligned GPLs for the interphase. Based upon the Mori-Tanaka method [24], the Hill’s parameters of the GPLs can be extracted from the following relations once the mechanical properties of the GPLs are in hand:

 

 

 

 

 

Now, the Hill’s parameters of the GPLs (i.e. , , ,  and ) can be easily extracted from Eqs. - once the mechanical properties of the GPLs are known. In above equations, the GPL was considered to behave as same as a transversely isotropic material. However, the epoxy matrix which was selected to be the matrix of the FRP is an isotropic linearly elastic solid. Hence, its Hill’s parameters can be derived using the following relations [23]:

 

 

 

 

Now, the Hill’s constants of the interphase must be determined, too. As expressed before, herein, the randomly oriented distribution will be considered for the GPLs inside the interphase. This assumption results in reaching to more reliable data. Using this assumption, the interphase will behave just as same as an isotropic solid. Based on the abovementioned assumption, the bulk moduli and shear moduli of the interphase can be simply obtained using the following formulas:

 

 

where  stands for the volume fraction of the GPLs in the interphase and  denotes the volume fraction of the polymeric matrix in it. Also, the terms , , , and  can be calculated using the following relations:

 

 

 

 

Now, the equivalent Young’s moduli and Poisson’s ratio of the interphase can be derived as follows:

 

 

In this stage, the moduli and Poisson’s ratio of all of the constituent materials of the composite are in hand. Therefore, the effective Young’s moduli and Poisson’s ratio of the composite, which is a nanocomposite in fact, can be simply calculated using the concept of the rule of the mixture:

 

 

The above moduli and Poisson’s ratio correspond with those of the non-porous CFRPs. In order to apply the effects of the existence of the porosities on the mechanical indices of the CFRP, a porosity-dependent micromechanical method will be utilized. In this stage, two major types of porosity distribution will be considered, namely symmetric and asymmetric. In the symmetric porosity distribution, the biggest pores are assumed to be in the neighborhood of the neutral axis of the structure; hence, this zone will be affected by the existence of the pores more than the other zones. Thus, the lowest moduli and Poisson’s ratio can be found to be in axes near the neutral plane of the plate. In the asymmetric distribution, the size of the pores is in its maximum value in one of the edges and it is in its maximum in another edge.

To apply the effects of porosities and satisfy the abovementioned physical concepts, the following relations can be expressed for the estimation of the Young’s moduli and shear moduli of the porous CFRPs:

 

 

where  is the porosity coefficient. Also, the  stands for the Poisson’s ratio of the porous material. To satisfy each of the symmetric and asymmetric porosity distributions, the following  functions must be employed:

 

Using the assumption of closed-cell porous materials [25, 26], the Poisson’s ratio of the material can be approximated using the below relation:

 

in which

 

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| E:\kar\Mehdi Taheri (Erfan UT)\2nd paper (Initial draft prepared)\Figures\Porous_a.jpgE:\kar\Mehdi Taheri (Erfan UT)\2nd paper (Initial draft prepared)\Figures\Porous_b.jpg**Fig. 1.** Variation of the Young’s moduli of the CFRP through-the-thickness direction for (a) symmetrically and (b) asymmetrically distributed pores in the material. |

In order to find out the way in which the stiffness of the CFRP can be influenced by existence of pores in the media, Fig. 1 is dedicated to plot the variation of the Young’s moduli of the material in any desired dimensionless thickness for various amounts of the porosity coefficient regarding for both symmetric and asymmetric distributions of porosities in the material. It can be simply understood that adding the porosity coefficient possesses a negative impact on the stiffness of the material and results in the reduction of the system’s moduli in any arbitrary thickness. In addition to the destroying impact of the porosity coefficient on the stiffness of the material, the pattern of the pores’ distribution affects the stiffness of the medium, too. Indeed, asymmetric-type pattern ruins the stiffness of the system more than the symmetric-type one. The physical reason of this phenomenon can be figured out looking at Fig. 1, exactly. In symmetric distribution, the minimum moduli correspond with the dimensionless thickness of zero and the maximum amount of the Young’s moduli will be at the top and bottom planes of the structure. However, in the asymmetric distribution, the top plane possesses maximum stiffness while the minimum stiffness of the system corresponds with the bottom plane of the structure.

In the future steps, it will be observed that the through-the-thickness rigidities of the system, which have a direct relation with the system’s buckling endurance, will be greater if the maximum amount of the moduli appears at the planes far from the neutral plane of the plate. Hence, it can be estimated that porous plates including symmetrically distributed pores will tolerate higher buckling loads in comparison with those containing asymmetrically distributed pores.

* 1. Constitutive equations

In this section, the stress-strain behaviors of the composite system will be expressed in mathematical language. The equivalent porous CFRP behaves like an isotropic linearly elastic solid. The constitutive equation of such materials can be expressed in the below form:

 

where  and  stand for the components of the second-order Cauchy stress and strain tensors, respectively; also,  corresponds with the components of the fourth-order elasticity tensor of the material. For a higher-order plate-type element, the above equation can be expressed in the following form:

 

in which

 

* 1. Higher-order shear deformation plate theory

This section is allocated to introduce the displacement field of the plate theory which will be utilized for the purpose of finding the governing equations of the problem. Herein, a refined-type HSDT will be employed in order to consider for the impacts of shear deflection of the structure free from utilizing any external shear correction coefficient as well as reducing the number of the independent variables from five in simple HSDTs to four. Based on the refined plate theory, the displacement field of the plate can be presented as [27]:

 

where  and  correspond with the axial and flexural displacements of the neutral plane of the plate, respectively. Also,  and  are bending and shear deflections, respectively. In above equation,  is the shape function which is responsible for the underestimation of both shear stress and strain through the thickness of the structure. In this paper, the expression presented in Ebrahimi *et al.* [27] will be selected for the shape function of the refined plate model. Following the definition of the infinitesimal strains of a continuous system in the continuum mechanics, the nonzero strains of the plate can be written in the below form [27]:

 

in which

 

In Eq. , we have .

* 1. Equations of motion

Now, the motion equations of the plate will be developed in this section. To this purpose, the energy-based principle of virtual work must be employed. Based on this principle, the variation of the total energy of the system must be equal with zero. Hence, the variation of the strain energy of the system must be calculated. The strain energy of a continuous system can be expressed in the following form:

 

In above equation,  is the total volume of the continua. The term  is generated from the double-contraction of the second-order stress and strain tensors of the system. According to the above equation and reminding the fact that the under observation structure is fabricated from a linearly elastic solid, the variation of the strain energy of the system can be presented in the following form:

 

Using the definition of the nonzero strains of the system, presented in Eq. , incorporated with Eq. , the variation of the strain energy of the plate can be formulated as below:

 

In above equation, the stress-resultants can be found using the following definitions:

 

Now, the variation of work done by the buckling load applied on the plate must be calculated. Considering the situation that a certain buckling load is applied on the structure in both longitudinal and flexural directions, the variation of work done by the buckling load can be presented in the following form:

 

where  stands for the buckling load applied on the structure. Now, the energy functional of the plate can be enriched using the definition of the principle of virtual work as follows:

 

Substituting for the stress-resultants from Eq. into Eq. and following the expressions which can be gathered using Eq. and also setting the coefficients of , ,  and  to zero, the non-trivial response of the system can be enriched and the Euler-Lagrange equations of the system can be obtained in the following form:

 

 

 

 

* 1. Governing equations

In this section, the motion equations enriched in the previous section will be combined with the constitutive equations of the composite material in order to find the governing equations of the plate in terms of the displacement field of the system.

Using the constitutive equation presented in Eq. incorporated with the definition of the stress-resultants of the plate introduced in Eq. , the stress-resultants can be presented in terms of the components of the displacement field of the structure as below:

 

In above equation, the through-the-thickness rigidities can be calculated following the below formulas:

 

Now, the governing equations of the plate can be enriched substituting Eq. into Eqs. -. Once the aforementioned substitution is accomplished, the governing equations of plates manufactured from porous CFRP can be achieved as below:

 

 

 

 

1. **Analytical solution**

In this stage, the Navier’s analytical solution will be introduced and implemented in order to find the buckling response of the system. Based on this method, all of the edges of the plate are simply supported. The solution function of this type of solution for refined higher-order plates can be presented as below:

 

Once the above equation is substituted into Eqs. -, the following equation can be attained:

 

in which  is the stiffness matrix and  stands for the amplitude vector and is . Solving the above equation corresponds with setting the determinant of it to zero, i.e.:

 

Once the above straight forward instructions are followed and Eq. is solved for , the buckling load of the plate can be achieved.

1. **Numerical results and discussion**

In this part of the paper, some numerical examples will be presented in order to see the effects of the involved variants on the buckling behaviors of the CFRP plate. Prior to any investigation, it is noteworthy that the length-to-thickness ratio of the plate is fixed on  in all of the following studies. Also, the below dimensionless form of the buckling load will be utilized in all of the future investigations:

 

The initial matrix of the nanocomposite is assumed to be epoxy. The material properties of the epoxy matrix and GPLs can be enriched reviewing the paper written by Pawlik *et al.* [23]. Also, the material properties of the CFs can be found in the open literature (e.g. see Ebrahimi and Dabbagh [28]).

* 1. Verification study

In this section, the validity of the presented model will be double checked. To find out the applicability of the presented methodology in approximation of the buckling load parameter of composite plates, the results of the comparison of the dimensionless buckling loads of functionally graded plates are tabulated in Table 1. According to this table, the results of this work are in a remarkable agreement with those reported by Zhao *et al.* [29]. The reason of the tiny difference between the results is that the HSDT of plates is utilized in the present study; whereas, Zhao *et al.* [29] used the FSDT. In addition, they solved the buckling problem on the basis of the FEM; however, in the present investigation, an analytical solution is utilized.

**TABLE 1** Comparison of the buckling loads of plates

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| Power-law term, n | Zhao *et al.* [29] | Present |
| 0.0 | 82.827 | 82.150 |
| 0.2 | 73.321 | 71.897 |
| 0.5 | 64.814 | 64.107 |
| 1.0 | 57.901 | 57.431 |
| 2.0 | 53.022 | 52.648 |
| 5.0 | 49.173 | 48.857 |

* 1. Effect of the porosity distribution

The main objective of drawing Fig. 2 is to show that which of the porosity distributions can affect the buckling response of the plate more than another one. In this figure, the variation of the buckling load of the porous CFRP plate against porosity coefficient is plotted for both symmetric and asymmetric porosity distributions. It can be figured out that the asymmetrically porous CFRP plates can tolerate smaller buckling loads in comparison with symmetrically porous ones. The reason of this reality is that the stiffness of the system will be more destroyed in the case of having pores distributed in the structure in an asymmetric manner rather than symmetric one. In fact, the Young’s moduli of the CFRP will be in its maximum value at the top and bottom surfaces once symmetric distribution state is satisfied and because of the higher importance of the surfaces far from the neutral plane of the plate in determination of the through-the-thickness rigidities of the plate, the static stability limit of the plate will be lesser influenced by the available pores in this case compared with the situation of having pores distributed in the media in an asymmetric manner.

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| E:\kar\Mehdi Taheri (Erfan UT)\2nd paper\Figure1.jpg**Fig. 2.** Variation of the dimensionless buckling load of porous CFRP square plates versus porosity coefficient for both symmetric and asymmetric porosity distributions (a/h=10, Vf=Vr=Vi=1%). |

* 1. Effect of volume fraction of the CFs

The second example is dedicated to the investigation of the impact of the volume fraction of the CFs on the stability response of the CFRP plates once both symmetrically and asymmetrically distributed pores are assumed to be available in the continua (see Fig. 3). According to this figure, it can be realized that the stability endurance of the plate can be improved while a larger amount of the CFs is utilized in the composition of the utilized composite material. The aforementioned trend is natural because the stiffness of the polymeric composite will be improved adding the content of the reinforcing CFs in the media due to the higher stiffness of the CFs in comparison with the polymeric matrix. Again, it can be seen that the slope of the reduction of the buckling load of the system in the case of considering asymmetric-type porosity distribution is greater than the case of considering symmetric-type porosity distribution.

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| E:\kar\Mehdi Taheri (Erfan UT)\2nd paper\Figure2a.jpgE:\kar\Mehdi Taheri (Erfan UT)\2nd paper\Figure2b.jpg**Fig. 3.** Variation of the dimensionless buckling load of porous CFRP square plates versus porosity coefficient for various volume fractions of CFs considering (a) symmetric and (b) asymmetric porosity distribution (a/h=10, Vr=Vi=1%). |

* 1. Effect of the volume fraction of the interphase

On the other hand, Fig. 4 undergoes with the study of the impact of the volume fraction of the GPLs-reinforced interphase on the stability response of the CFRP plate. It can be seen that as we guessed and stated before, the existence of the GPL coatings can improve the stiffness of the interphase between the fiber and matrix which will be lead to observing an increment in the buckling load of the plate. In fact, adding the volume fraction of the interphase makes the plate stronger against applied buckling excitations and results in the enhancement of the static stability performance of the plate. As expressed in the interpretation of the previous figures, it can be another time seen that plates with symmetrically distributed pores are better candidates for the cases that the continuous composite system is going to be subjected to extreme loading conditions.

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| E:\kar\Mehdi Taheri (Erfan UT)\2nd paper\Figure3a.jpgE:\kar\Mehdi Taheri (Erfan UT)\2nd paper\Figure3b.jpg**Fig. 4.** Variation of the dimensionless buckling load of porous CFRP square plates versus porosity coefficient for various volume fractions of interphase considering (a) symmetric and (b) asymmetric porosity distribution (a/h=10, Vr=Vf=1%). |

* 1. Effect of the volume fraction of the GPLs in the interphase

As the final example, the variation of the dimensionless buckling load of the plate versus porosity coefficient is depicted in Fig. 5 once the volume fraction of the GPLs in the interphase is varied from 0.1% to 2.0%. Clearly, the enhancement of the mechanical endurance of the system can be seen because the stiffness of the attained composite will be grown in the case of adding the content of the available GPLs in the composition of the CFRP. So, it is a very interesting alternative to use nanosize GPLs as coating on the CF in the CFRPs for the cases that the designed device is assumed to be subjected to severe working conditions. Besides, it can be understood that asymmetric-type distribution of the pores will affect the total stiffness of the plate more that the symmetric-type one.

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| E:\kar\Mehdi Taheri (Erfan UT)\2nd paper\Figure4a.jpgE:\kar\Mehdi Taheri (Erfan UT)\2nd paper\Figure4b.jpg**Fig. 5.** Variation of the dimensionless buckling load of porous CFRP square plates versus porosity coefficient for various volume fractions of GPLs in the interphase considering (a) symmetric and (b) asymmetric porosity distribution (a/h=10, Vi=Vf=1%). |

1. **Conclusion**

The proposed manuscript was arranged for the purpose of showing the impact of adding GPL coatings on the CFs in a CFRP on the stability responses of the plates fabricated from CFRP. In addition to adding GPL coatings on the CFs, the impact of the existence of porosities in the CFRP on the equivalent stiffness of the system was included, too. On the other hand, the refined-type HSDT of the plates was used in order to reach the governing equations of the plate. Thereafter, the virtual work’s principle was employed to reach the governing equations. Then, the Navier-type solution was selected for the purpose of solving the buckling problem of a refined porous CFRP plate. A brief review of the most crucial highlights of this work will be listed below to put emphasis on the importance of the involved terms in the approximation of the buckling behaviors of the continua:

* Adding the volume fraction of the interphase will result in an increase in the buckling endurance of the plate.
* The more is the content of the available GPLs in the composite the higher will be the buckling load which can be tolerated by the plate.
* Naturally, CFRPs with higher amount of the CFs will endure greater static excitations.
* Existence of pores in the media will affect the buckling load of the structure in a negative manner.
* Asymmetric-type porosity distribution will destroy the stiffness of the composite structure more than symmetric-type one.
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