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Propagation behaviors of guided waves in graphene platelet reinforced metal foam plates

Wubin Shan[1,2], Hao Zhong[1], Nannan Zhang[1] and Guilin She*[3]

[1]*Hunan Electrical College of Technology, School of elevator engineering, Xiangtan 411100, China*
[2]*College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China*
[3]*College of Mechanical and Vehicle Engineering, Chongqing University, Chongqing 400044, China*

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Abstract. At present, the research on wave propagation in graphene platelet reinforced composite plates focuses on the propagation behavior of bulk waves, in which the effect of boundary condition is ignored, there is no literature report on propagation behaviors of guided waves in graphene platelet reinforced metal foams (GPLRMF) plates. In fact, wave propagation is affected by boundary conditions, so it is necessary to study the propagation characteristics of guided waves. The aim of this paper is to solve this problem. The effective performance of the material was calculated using the mixing law. Equations of motion of GPLRMF plate is derived by using Hamilton's principle. Then, the eigenvalue method is used to obtain the expressions of bending wave, shear wave and longitudinal wave, and the degradation verification is carried out. Finally, the effects of graphene platelets (GPLs) volume fraction, elastic foundation, porosity coefficient, GPLs distribution types and porosity distribution types on the dispersion relations are studied. We find that these factors play an important role in the propagation characteristics and phase velocity of guided waves.

Keywords: galerkin principle; graphene platelets; metal foams; phase velocity; platephase velocity; wave propagation

1. Introduction

At present, studying the static and dynamic behavior of functionally graded or reinforced structures has become a hot research topic, such as literatures (Ahmadi *et al.* 2021, Allahkarami and Tohidi 2022, Aris and Ahmadi 2022, Assie *et al.* 2023, Hendi *et al.* 2022, Malikan *et al.* 2022, Mahani *et al.* 2020, Martins *et al.* 2021, Melaibari *et al.* 2023, Nguyen *et al.* 2021, Phuong *et al.* 2022, 2021, Ramezani *et al.* 2022, Saiah *et al.* 2022, Shahgholian-Ghahfarokhi *et al.* 2021, Salehi *et al.* 2022, Trang *et al.* 2022, Van Doan *et al.* 2022, Alnujaie *et al.* 2021, Gan and She 2023, She 2021, She and Li 2022, Xu and She 2022, Zhang *et al.* 2023c, 2023d, Ahmadi and Foroutan 2021, Abuteir and Boutagouga 2022, Basha *et al.* 2022, Wang and Zhang 2022, Alazwari *et al.* 2022, Daikh *et al.* 2021, 2023, Mohamed *et al.* 2023, Chen *et al.* 2022a, b, Ding *et al.* 2021, 2023a, b, Ding *et al.* 2023a, b, c, 2022a, b, Gan and She 2023, Gan *et al.* 2023, Li *et al.* 2023, She 2021, She and Ding 2023, She and Li 2022, She *et al.* 2021, 2022, Wu and She 2023, Xu and She 2022, 2023, Xu *et al.* 2023a, b, c, 2024, Zhang and She 2022, 2023a, b, 2024, Zhang *et al.* 2021, 2022, 2023a, b, c, d, e, Zhao *et al.* 2022a, b, Ding and She 2023c, Ding *et al.* 2023d, Gan and She 2024, Shan and She 2023), but there are relatively few literatures on wave propagation problems.

For example, Xiang *et al.* (2023) analyzed the wave propagation phenomenon of graphene oxide powder-strengthened composite curved beam. Gan *et al.* (2023) discussed the wave propagation of GPLRMF circular plates using Laplace integral method. Ebrahimi and Seyfi (2022) studied wave propagation behaviors of GPLRMF plates rested on an elastic medium subjected to hygro-thermal effects. Hashemi-Nejad *et al.* (2022) examined wave propagation in GPLRMF composite rotating thin-walled blades with nonuniform and uniform distributions of graphene platelet. Babaei *et al.* (2021) performed the stress wave propagation analysis of GPLRMF joined conical-cylindrical-conical shell using the modified Halpin-Tsai estimation. Al Mukahal *et al.* (2021) presented wave propagation of GPLRMF curved beams having auxetic core with viscoelastic foundation with the aid of the differential quadrature method. Zenkour and Sobhy (2022) investigated the axial magnetic effect on wave propagations in graphene platelet-reinforced beams in nano scale. Li and Han (2021) analyzed the guided waves propagation of graphene-epoxy core and piezoelectric shells using the Chebyshev spectral element method. Li *et al.* (2020) presented wave propagation analysis in piezoelectric graphene platelets plates with the semi-analytical method. Li and Han (2021) discussed wave propagation in graphene reinforced composite annular plates via semi-analytical method. Ebrahimi and Dabbagh (2020) developed a nonlocal strain gradient theory to analyze wave dispersions of axially loaded graphene sheets resting on the viscoelastic foundations. Ebrahimi *et al.* (2021) analyzed wave propagation of spinning GPLRMF cylindrical shell at nano scale.

*Corresponding author, Associate Professor
E-mail: sheguilin@cqu.edu.cn

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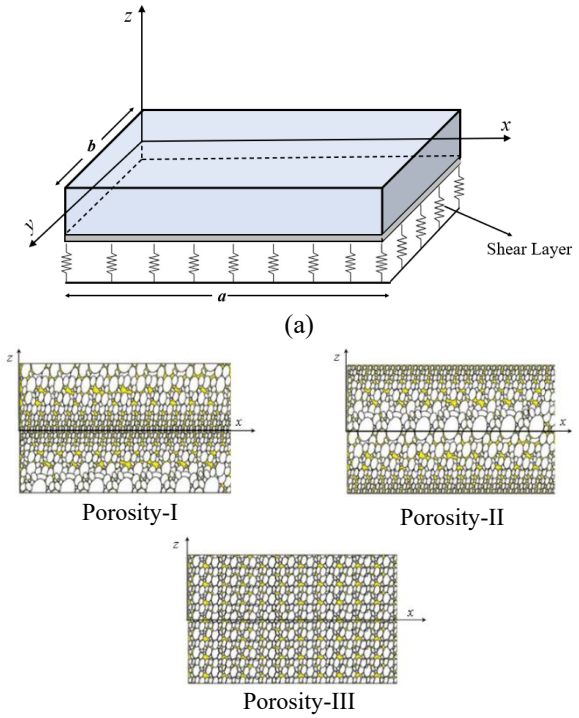

Fig. 1 A sketch of GPLRMF plate resting on elastic foundation (Modified from Zhang *et al.* 2023b, Ding and She 2023a)

At present, there is no literature report on propagation behaviors of guided waves in graphene platelet plate reinforced metal foam (GPLRMF) plates. Through literature search, we can see that there is very little papers about the propagation of guided waves, and currently, there are no literature reporting on the guided wave in the GPLRMF plates. In fact, wave propagation is affected by boundary conditions, the aim of this paper is to solve this problem.

2. Wave equations

Illustrated in Fig. 1 is the schematic diagram of a GPLRMF plate, in addition the plate rests on two-parameters elastic foundation $p(x,y)=k_w w-k_s\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right)$.

The material characteristics may be expressed as (Kitipornchai *et al.* 2017)

$$E(z,T)=\begin{cases}E^{\#}\left[1-\mathrm{e}_1\cos(\pi z/h)\right], & (\text{Porosity-I})\\ E^{\#}\left\{1-\mathrm{e}_2\left[1-\cos(\pi z/h)\right]\right\}, & (\text{Porosity-II})\\ E^{\#}\mathrm{e}_3, & (\text{Porosity-III})\end{cases}$$
$$\rho(z,T)=\begin{cases}\rho^{\#}\left[1-\mathrm{e}_{m1}\cos(\pi z/h)\right], & (\text{Porosity-I})\\ \rho^{\#}\left\{1-\mathrm{e}_{m2}\left[1-\cos(\pi z/h)\right]\right\}, & (\text{Porosity-II})\\ \rho^{\#}\mathrm{e}_{m3}, & (\text{Porosity-III})\end{cases} \quad (1)$$
$$\alpha(z)=\alpha^{\#}$$
$$\mu(z)=\mu^{\#}$$

In which (Kitipornchai *et al.* 2017)

$$E^{\#}=\frac{3}{8}\left(\frac{1+\zeta_L V_{GPL}\eta_L}{1-\eta_L V_{GPL}}\right)\times E_M+\frac{5}{8}\left(\frac{1+\zeta_W V_{GPL}\eta_W}{1-\eta_W V_{GPL}}\right)\times E_M$$
$$\begin{bmatrix}\rho^{\#}\\ \alpha^{\#}\\ \mu^{\#}\end{bmatrix}=V_{GPL}\begin{bmatrix}\rho_{GPL}\\ \alpha_{GPL}\\ \mu_{GPL}\end{bmatrix}+(1-V_{GPL})\begin{bmatrix}\rho_M\\ \alpha_M\\ \mu_M\end{bmatrix} \quad (2)$$

In addition (Kitipornchai *et al.* 2017)

$$\frac{E(z,T)}{E_c}=\left[\frac{\rho(z)}{\rho_c}\right]^2 \quad (3)$$

$$\begin{cases}1-e_{\mathrm{m}1}\cos(\pi z/h)=\sqrt{1-e_1\cos(\pi z/h)}\\ 1-e_{\mathrm{m}2}\left[1-\cos(\pi z/h)\right]=\sqrt{1-e_2\left[1-\cos(\pi z/h)\right]}\\ e_{\mathrm{m}3}=\sqrt{e_3}\end{cases} \quad (4)$$

Due to the fact (Zhang *et al.* 2023b, Ding and She 2023a)

$$\int_0^{\frac{h}{2}}\sqrt{1-e_1\cos(\pi z/h)}dz=\int_0^{\frac{h}{2}}\sqrt{e_3}dz=\int_0^{\frac{h}{2}}\sqrt{1-e_2\left[1-\cos(\pi z/h)\right]}dz \quad (5)$$

Considering that (Zhang *et al.* 2023b, Ding and She 2023a)

$$V_{GPL}=\begin{cases}Si_1\left[1-\cos(\pi z/h)\right], & (\text{GPL-A})\\ Si_2\cos(\pi z/h), & (\text{GPL-B})\\ Si_3, & (\text{GPL-C})\end{cases} \quad (6)$$

Herein, the value of coefficients Si_1, Si_2, and Si_3 refers to Ref. (Kitipornchai *et al.* 2017).

The adopted displacement field is (Sun and Luo 2012)

$$\begin{aligned}u&=u_0(x,y,t)+z\varphi_x(x,y,t)\\ v&=v_0(x,y,t)+z\varphi_y(x,y,t)\\ w&=w_0(x,y,t)\end{aligned} \quad (7)$$

here, u_0, v_0, w_0 are the plate displacements, φ_x and φ_y are the mid-plane rotation. The strains are (Sun and Luo 2012)

$$\varepsilon_x=z\frac{\partial\varphi_x}{\partial x}+\frac{\partial u_0}{\partial x},\varepsilon_y=z\frac{\partial\varphi_y}{\partial y}+\frac{\partial v_0}{\partial y},$$
$$\varepsilon_{xy}=z\left(\frac{\partial\varphi_x}{\partial y}+\frac{\partial\varphi_y}{\partial x}\right)+\frac{\partial u_0}{\partial y}+\frac{\partial v_0}{\partial x}, \quad (8)$$
$$\varepsilon_{xz}=\frac{\partial w_0}{\partial x}+\varphi_x,\varepsilon_{yz}=\frac{\partial w_0}{\partial y}+\varphi_y.$$

The stress-strain relationship is,

$$\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \sigma_{xy}\\ \sigma_{xz}\\ \sigma_{yz}\end{Bmatrix}=\begin{bmatrix}\frac{E(z)}{1-\nu^2} & G(z) & 0 & 0 & 0\\ G(z) & \frac{E(z)}{1-\nu^2} & 0 & 0 & 0\\ 0 & 0 & G(z) & 0 & 0\\ 0 & 0 & 0 & \frac{5}{6}G(z) & 0\\ 0 & 0 & 0 & 0 & \frac{5}{6}G(z)\end{bmatrix}\begin{Bmatrix}\frac{\partial u_0}{\partial x}+z\frac{\partial \varphi_x}{\partial x}\\ \frac{\partial v_0}{\partial y}+z\frac{\partial \varphi_y}{\partial y}\\ \frac{\partial u_0}{\partial y}+\frac{\partial v_0}{\partial x}+z(\frac{\partial \varphi_x}{\partial y}+\frac{\partial \varphi_y}{\partial x})\\ \varphi_x+\frac{\partial w_0}{\partial x}\\ \varphi_y+\frac{\partial w_0}{\partial y}\end{Bmatrix} \tag{9}$$

The stress resultants and couples have the following form,

$$\begin{aligned}&N_x=A_{11}\frac{\partial u_0}{\partial x}+A_{12}\frac{\partial v_0}{\partial y},N_y=A_{12}\frac{\partial u_0}{\partial x}+A_{22}\frac{\partial v_0}{\partial y},\\ &N_{xy}=A_{66}(\frac{\partial u_0}{\partial y}+\frac{\partial v_0}{\partial x}),M_x=D_{11}\frac{\partial \varphi_x}{\partial x}+D_{12}\frac{\partial \varphi_y}{\partial y},\\ &M_y=D_{12}\frac{\partial \varphi_x}{\partial x}+D_{22}\frac{\partial \varphi_y}{\partial y},Q_x=A_{44}(\varphi_x+\frac{\partial w_0}{\partial x}),\\ &Q_y=A_{55}(\varphi_y+\frac{\partial w_0}{\partial y}).\end{aligned} \tag{10}$$

in which (Sun and Luo 2012)

$$\begin{aligned}&A_{11}=A_{22}=\int_{-\frac{h}{2}}^{\frac{h}{2}}\frac{E(z)}{1-\nu^2}dz,A_{12}=\int_{-\frac{h}{2}}^{\frac{h}{2}}\frac{\nu E(z)}{1-\nu^2}dz,A_{66}=\int_{-\frac{h}{2}}^{\frac{h}{2}}G(z)\,dz,\\ &A_{44}=A_{55}=\gamma^2A_{66},D_{11}=D_{22}=\int_{-\frac{h}{2}}^{\frac{h}{2}}\frac{z^2E(z)}{1-\nu^2}dz,\\ &D_{12}=\int_{-\frac{h}{2}}^{\frac{h}{2}}\frac{z^2\nu E(z)}{1-\nu^2}dz,D_{66}=\int_{-\frac{h}{2}}^{\frac{h}{2}}z^2G(z)\,dz.\end{aligned} \tag{11}$$

Using the Euler-Lagrange principle, the motion equations can be obtained as (Sun and Luo 2012)

$$\begin{aligned}&\frac{\partial N_x}{\partial x}+\frac{\partial N_{xy}}{\partial y}=I_0\frac{\partial^2u_0}{\partial t^2},\\ &\frac{\partial N_y}{\partial y}+\frac{\partial N_{xy}}{\partial x}=I_0\frac{\partial^2v_0}{\partial t^2},\\ &\frac{\partial Q_x}{\partial x}+\frac{\partial Q_y}{\partial y}+\frac{\partial}{\partial x}(N_x\frac{\partial w}{\partial x}+k_s\frac{\partial w}{\partial x}+N_{xy}\frac{\partial w}{\partial y})\\ &+\frac{\partial}{\partial y}(N_y\frac{\partial w}{\partial y}+k_s\frac{\partial w}{\partial y}+N_{xy}\frac{\partial w}{\partial x})+k_ww=I_0\frac{\partial^2w_0}{\partial t^2},\\ &\frac{\partial M_x}{\partial x}+\frac{\partial M_{xy}}{\partial y}-Q_x=I_2\frac{\partial^2\varphi_x}{\partial t^2},\\ &\frac{\partial M_y}{\partial y}+\frac{\partial M_{xy}}{\partial x}-Q_y=I_2\frac{\partial^2\varphi_y}{\partial t^2}.\end{aligned} \tag{12}$$

Herein, $(I_0,I_2)=\int_{-\frac{h}{2}}^{\frac{h}{2}}\rho(z)(1,z^2)\,\mathrm{d}z$.

Using Eq. (10), Eq. (12) becomes

$$\begin{aligned}&A_{11}\frac{\partial^2u_0}{\partial x^2}+A_{12}\frac{\partial^2v_0}{\partial x\partial y}+A_{66}(\frac{\partial^2u_0}{\partial y^2}+\frac{\partial^2v_0}{\partial x\partial y})=I_0\frac{\partial^2u_0}{\partial t^2},\\ &A_{12}\frac{\partial^2u_0}{\partial x\partial y}+A_{22}\frac{\partial^2v_0}{\partial y^2}+A_{66}(\frac{\partial^2u_0}{\partial x\partial y}+\frac{\partial^2v_0}{\partial x^2})=I_0\frac{\partial^2v_0}{\partial t^2},\\ &A_{44}(\frac{\partial\varphi_x}{\partial x}+\frac{\partial^2w_0}{\partial x^2})+A_{55}(\frac{\partial\varphi_y}{\partial y}+\frac{\partial^2w_0}{\partial y^2})+K_s\left(\frac{\partial^2w_0}{\partial x^2}+\frac{\partial^2w_0}{\partial y^2}\right)\\ &+k_ww=I_0\frac{\partial^2w_0}{\partial t^2},\\ &D_{11}\frac{\partial^2\varphi_x}{\partial x^2}+D_{12}\frac{\partial^2\varphi_y}{\partial x\partial y}+D_{66}(\frac{\partial^2\varphi_x}{\partial y^2}+\frac{\partial^2\varphi_y}{\partial x\partial y})-A_{44}(\varphi_x+\frac{\partial w_0}{\partial x})=I_2\frac{\partial^2\varphi_x}{\partial t^2},\\ &D_{12}\frac{\partial^2\varphi_x}{\partial x\partial y}+D_{22}\frac{\partial^2\varphi_y}{\partial y^2}+D_{66}(\frac{\partial^2\varphi_x}{\partial x\partial y}+\frac{\partial^2\varphi_y}{\partial x^2})-A_{55}(\varphi_y+\frac{\partial w_0}{\partial y})=I_2\frac{\partial^2\varphi_y}{\partial t^2}.\end{aligned} \tag{13}$$

3. Solution method

Considering clamped supported ends, the following solutions may be adopted (Sun and Luo 2012)

$$\begin{aligned}&u_0(x,y,t)=\sum_{m,n=1,3,5...}^{\infty}u_{mn}(t)\sin(\frac{m\pi}{a}x)\sin(\frac{n\pi}{b}y)\\ &\times\left[e^{\mathrm{i}(\kappa_1x+\kappa_2y+\omega t)}+e^{\mathrm{i}(\kappa_1x+\kappa_2y-\omega t)}\right],\\ &v_0(x,y,t)=\sum_{m,n=1,3,5...}^{\infty}v_{mn}(t)\sin(\frac{m\pi}{a}x)\sin(\frac{n\pi}{b}y)\\ &\times\left[e^{\mathrm{i}(\kappa_1x+\kappa_2y+\omega t)}+e^{\mathrm{i}(\kappa_1x+\kappa_2y-\omega t)}\right],\\ &w_0(x,y,t)=\sum_{m,n=1,3,5...}^{\infty}w_{mn}(t)[1-\cos(\frac{2m\pi}{a}x)][1-\cos(\frac{2n\pi}{b}y)]\\ &\times\left[e^{\mathrm{i}(\kappa_1x+\kappa_2y+\omega t)}+e^{\mathrm{i}(\kappa_1x+\kappa_2y-\omega t)}\right],\\ &\varphi_x(x,y,t)=\sum_{m,n=1,3,5...}^{\infty}\varphi_{mn}^x(t)\sin(\frac{2m\pi}{a}x)[1-\cos(\frac{2n\pi}{b}y)]\\ &\times\left[e^{\mathrm{i}(\kappa_1x+\kappa_2y+\omega t)}+e^{\mathrm{i}(\kappa_1x+\kappa_2y-\omega t)}\right],\\ &\varphi_y(x,y,t)=\sum_{m,n=1,3,5...}^{\infty}\varphi_{mn}^y(t)[1-\cos(\frac{2m\pi}{a}x)]\sin(\frac{2n\pi}{b}y)\\ &\times\left[e^{\mathrm{i}(\kappa_1x+\kappa_2y+\omega t)}+e^{\mathrm{i}(\kappa_1x+\kappa_2y-\omega t)}\right].\end{aligned} \tag{14}$$

In which, [u_{mn} , v_{mn} , w_{mn} , φ_{mn}^x , φ_{mn}^y] are wave amplitudes, [κ_1 , κ_2] are wave numbers. Using Eq. (14) and Galerkin principle, Eq. (13) becomes (She 2021)

$$\left(\begin{bmatrix}K_{11}&K_{12}&K_{13}&K_{14}&K_{15}\\ K_{21}&K_{22}&K_{23}&K_{24}&K_{25}\\ K_{31}&K_{32}&K_{33}&K_{34}&K_{35}\\ K_{41}&K_{42}&K_{43}&K_{44}&K_{45}\\ K_{51}&K_{52}&K_{53}&K_{54}&K_{55}\end{bmatrix}-\omega^2\begin{bmatrix}I_0&0&0&0&0\\ 0&I_0&0&0&0\\ 0&0&9I_0&0&0\\ 0&0&0&3I_2&0\\ 0&0&0&0&3I_2\end{bmatrix}\right) \tag{15}$$

$$[u_{11},v_{11},w_{11},\varphi_{11}^x,\varphi_{11}^y]^{\mathrm{T}}=0$$

In which

$$\begin{aligned}&K_{11}=A_{11}\left(\lambda_1^2+\kappa_1^2\right)+A_{66}(\mu_1^2+\kappa_2^2),\\ &K_{12}=K_{21}=(A_{12}+A_{66})\kappa_1\kappa_2,\\ &K_{13}=K_{31}=K_{14}=K_{41}=K_{15}=K_{51}=K_{23}\\ &=K_{32}=K_{24}=K_{42}=K_{25}=K_{52}=0,\\ &K_{22}=A_{22}\left(\mu_1^2+\kappa_2^2\right)+A_{66}\left(\lambda_1^2+\kappa_1^2\right),\\ &K_{33}=9\left[\left(A_{44}+K_s\right)\kappa_1^2+\left(A_{55}+K_s\right)\kappa_2^2\right]\\ &\quad+12\left[\left(A_{44}+K_s\right)\lambda_1^2+\left(A_{55}+K_s\right)\mu_1^2\right]+K_w,\\ &K_{34}=K_{43}=6A_{44}\lambda_1,K_{35}=K_{53}=6A_{55}\mu_1,\\ &K_{44}=3D_{11}\left(4\lambda_1^2+\kappa_1^2\right)+D_{66}\left(4\mu_1^2+\kappa_2^2\right)+3A_{44},\\ &K_{45}=K_{54}=4\left(D_{12}+D_{66}\right)\lambda_1\mu_1,\\ &K_{55}=3D_{22}\left(4\mu_1^2+\kappa_2^2\right)+D_{66}\left(4\lambda_1^2+\kappa_1^2\right)+3A_{55}.\end{aligned}$$

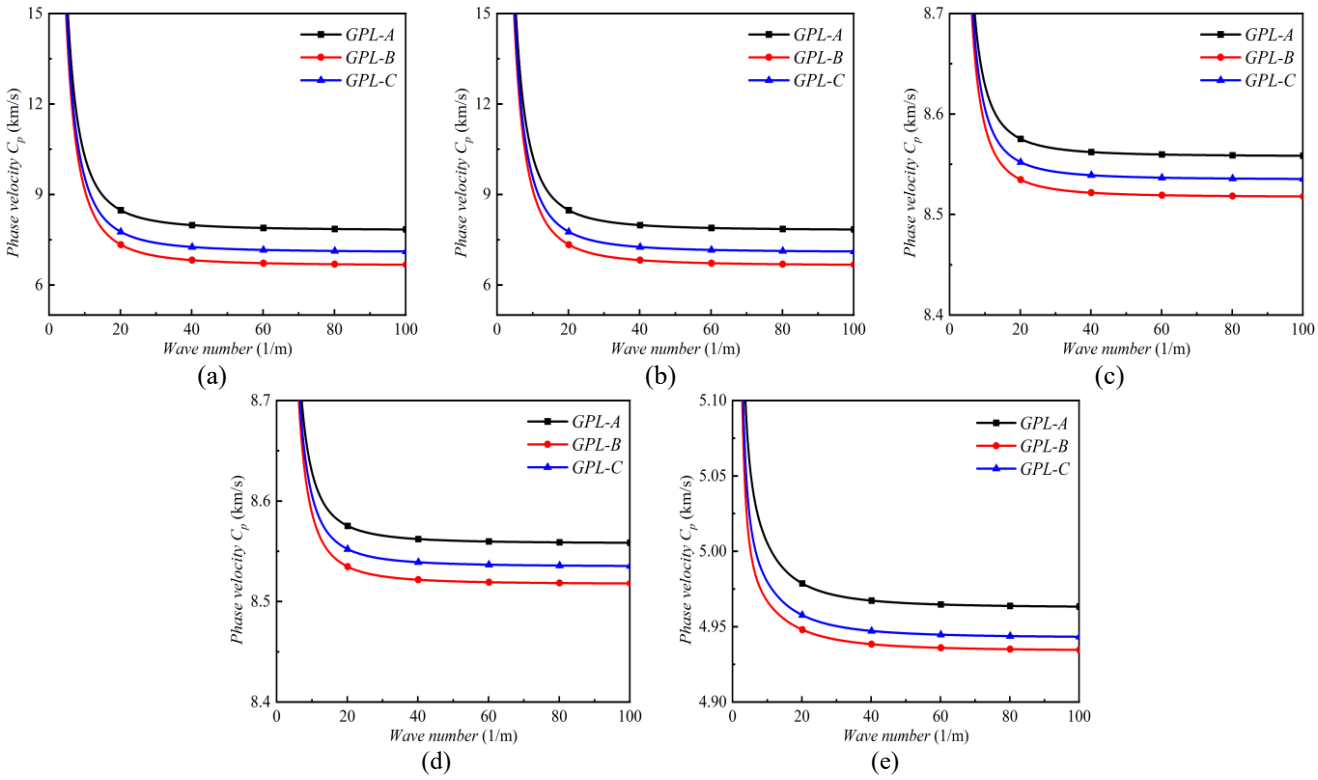

Fig. 2 Effect of GPLs distribution types (a=b=2 m, h=0.2 m, k_w=0, k_s=0, Porosity-I, W_{gpl}=1%, e_1=0.2)

in which, $\lambda_1=\frac{\pi}{a},\mu_1=\frac{\pi}{b}$. If Eq. (15) has a non-zero solution, then the determinant of the matrix of Eq. (15) must be equal to 0, from which five different solutions can be obtained. The largest two solutions correspond to shear waves, the smallest solution corresponds to bending waves, and the other two solutions correspond to longitudinal waves. We can get the expressions of phase velocity $C_p=\frac{\omega}{\kappa}$ from Eq. (15) with the consideration of $\kappa=\kappa_1=\kappa_2$.

4. Numerical analyses

In the next part, the adopted geometrical parameters and material properties are (Gan *et al*. 2023, Gan and She 2023): E_m=200 GPa, μ_m=0.33, ρ_m=7850 kg/m^3, E_{GPL}=1010 GPa, μ_{GPL}=0.186, ρ_{GPL}=1060 kg/m^3, t_{GPL}=1.5×10-9 m, w_{GPL}=2.5×10-6 m, l_{GPL}=1.5×10-6 m.

In the following analysis, in Figs. 2 to 6, the first and second figures are shear waves, the third and fourth figures are longitudinal waves, and the fifth figure is bending waves.

In Fig. 2, we studied the impact of three GPLs distribution types, GPL-A, GPL-B and GPL-C, on wave propagation. As seen, when the wave number is small, the phase velocity decreases sharply with the increase of the wave number. This indicates that only when the wave number is very small, the wave number have a significant impact on the phase velocity. When the wave number increases to a certain value, the phase velocity tends to be stable, and at this time, the value of the bending wave is the smallest. This is because, similar to vibration problems, bending waves are the most important issue which should be considered in wave propagation problems. Additionally, the values of phase velocity can be ranked in order as follows: GPL-A>GPL-C>GPL-B. This is because for the GPL-A type, the content of GPLs is highest on the upper and lower surfaces of the plate, while for the GPL-B type, the content of GPLs is lowest on the upper and lower surfaces of the plate. In addition, when the wave number is fixed, the phase velocity of shear wave is greater than the phase velocity of longitudinal wave and the phase velocity of bending wave.

In Fig. 3, we studied the impact of three porosity distribution types on wave propagation problems. It can be seen that when the wave number is small, the phase velocity decreases sharply with the increase of wave number. When the wave number increases to a certain value, the phase velocity tends to be stable, and at this time, the value of bending wave is the smallest; When the wave number keeps unchanged, the values of phase velocity can be ranked in order as follows: Porosity-I>Porosity-III>Porosity-II. This is because for the Porosity-I type, the porosity is highest on the upper and lower surfaces of the plate, while for the Porosity-II type, the porosity is lowest on the upper and lower surfaces of the plate.

In Fig. 4, we studied the effect of porosity coefficient. As seen, under a certain wave number, the phase velocity is the minus function of the porosity coefficient, that is, the larger the porosity coefficient, the smaller the phase velocity. As expected, the higher the porosity coefficient, the lower the stiffness of the plate, resulting in a decrease in

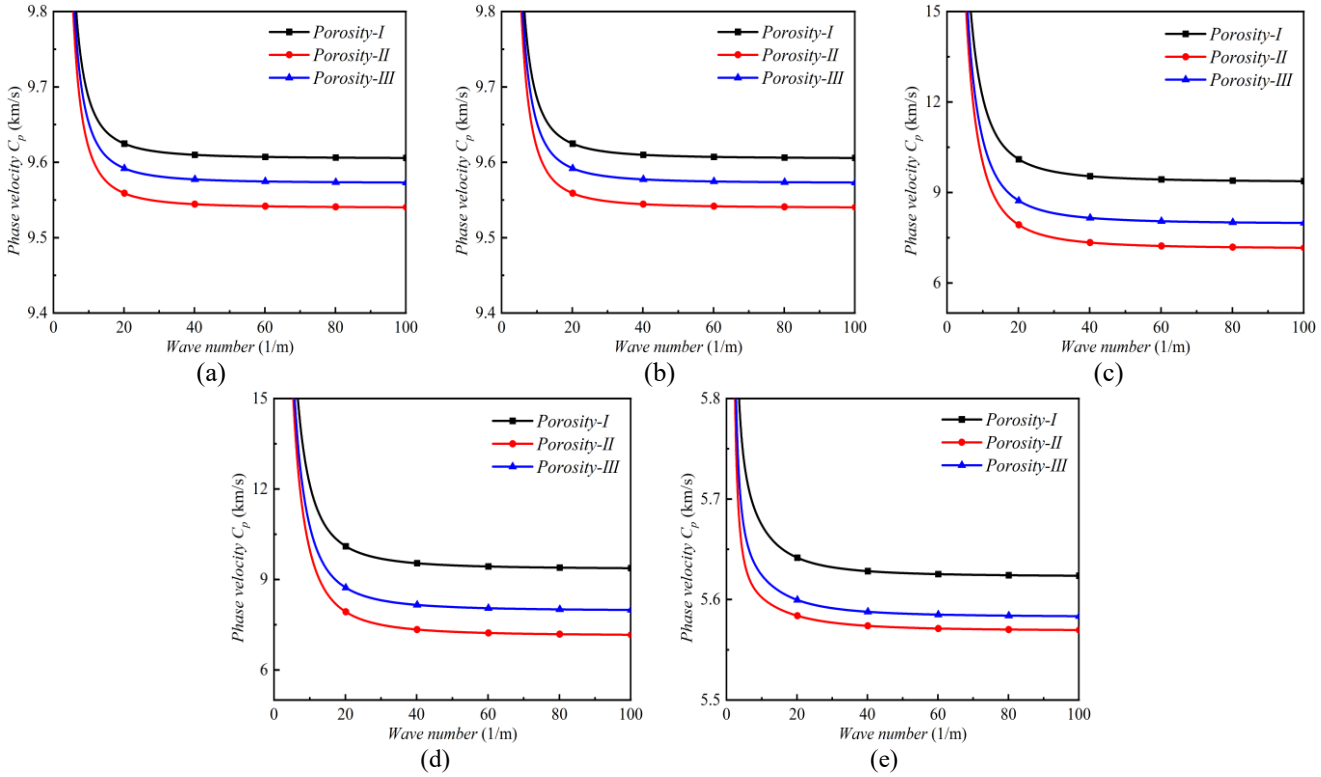

Fig. 3 Effect of porosity distribution types (a=b=2 m, h=0.2 m, k_w=0, k_s=0,GPL-A, W_{gpl}=1%, e_1=0.2)

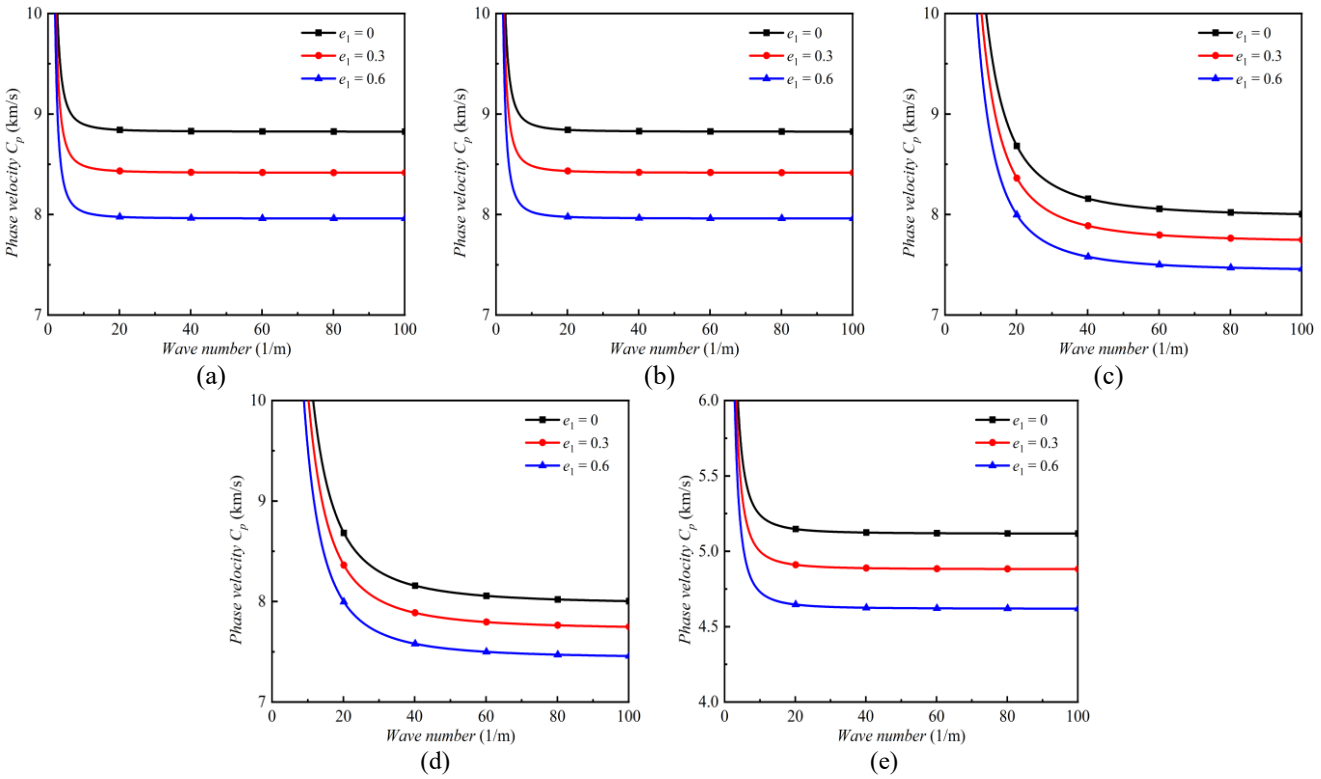

Fig. 4 Effect of porosity coefficient (a=b=2 m, h=0.2 m, k_w=0, k_s=0, Porosity-I, W_{gpl}=1%, GPL-A)

phase velocity. In addition, at the same wave number, the phase velocity of shear wave is the largest, followed by longitudinal wave, and bending wave.

In Fig. 5, we studied the impact of GPLs weight fraction on wave propagation problems. As seen, the GPLs weight fraction play an important role in wave propagation. Under

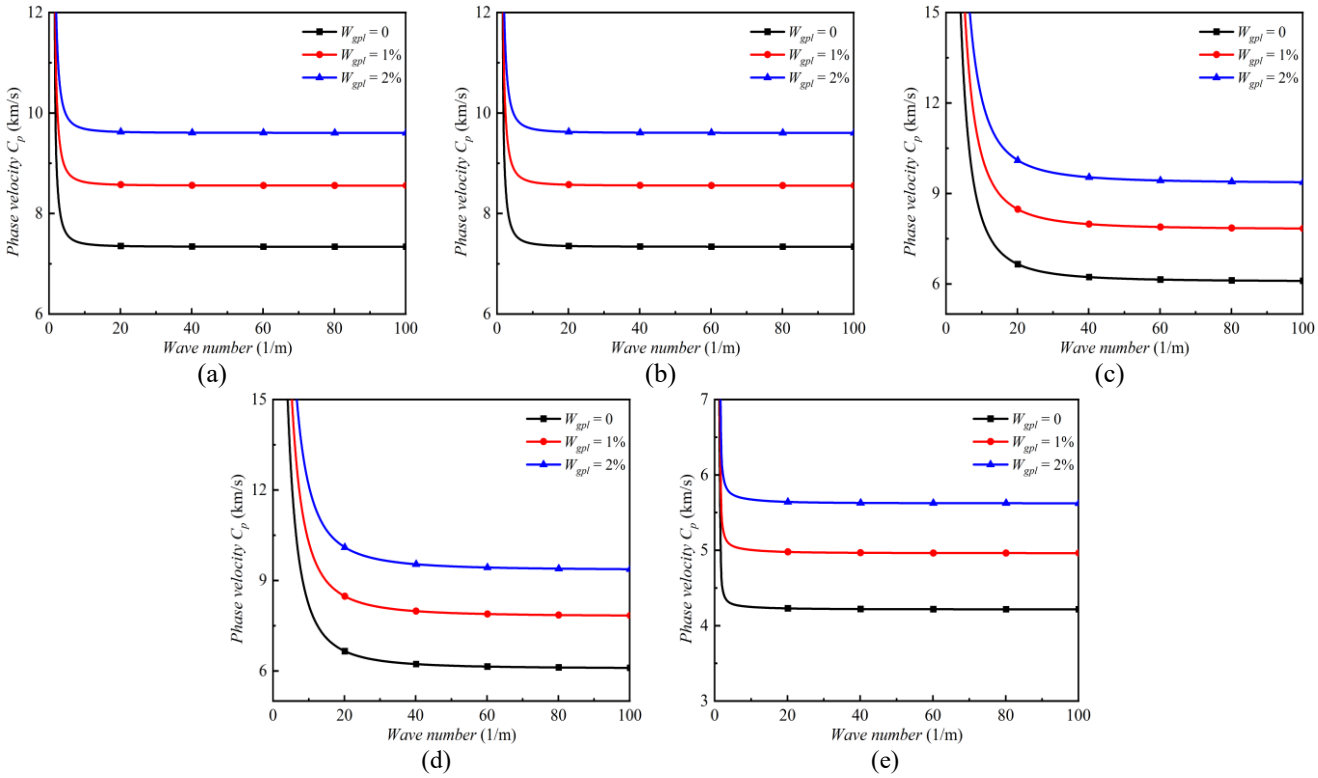

Fig. 5 Effect of porosity coefficient (a=b=2 m, h=0.2 m, k_w=0, k_s=0, Porosity-I, GPL-A, e_1=0.2)

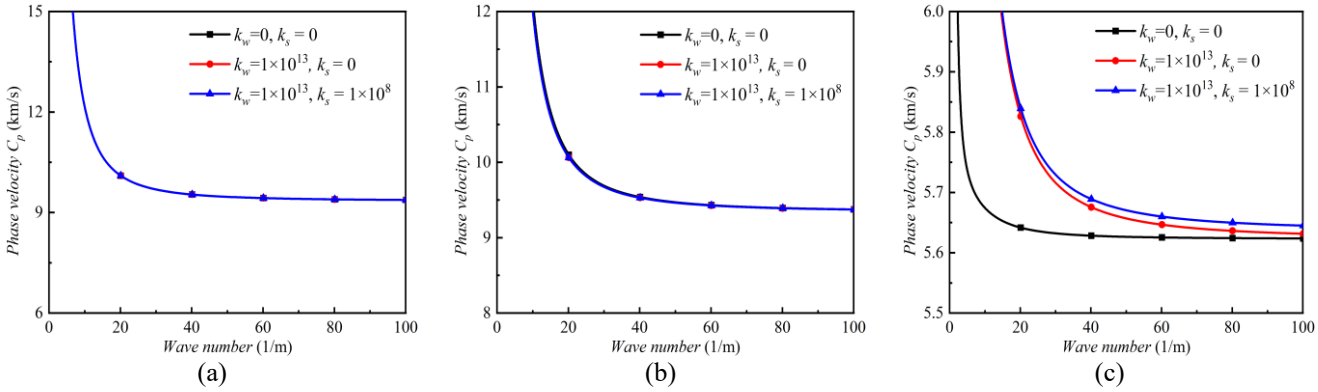

Fig. 6 Effect of porosity coefficient (a=b=2 m, h=0.2 m, GPL-A, Porosity-I, W_{gpl}=1%, e_1=0.2)

a certain wave number, the phase velocity increases significantly with the increase of GPLs weight fraction. As expected, the higher the GPLs weight fraction, the higher the stiffness of the plate, resulting in an increase in phase velocity. In addition, the larger the wave number, the smaller the phase velocity. In addition, at the same wave number, the phase velocity of shear wave is the largest, followed by longitudinal wave and bending wave.

In Fig. 6, we studied the impact of elastic foundation on wave propagation. It can be seen that the impact of elastic foundation on shear wave is negligible, but the impact of elastic foundation on bending wave is more significant. When k is large, the larger the k_w or k_s, the greater the phase velocity. This is because, similar to vibration problems, elastic foundations only have a significant impact on bending vibration problems or the propagation of bending waves.

5. Conclusions

As an innovative attempt, the propagation of longitudinal, bending and shear waves in GPLRMF plates resting on elastic foundations are studied in this paper. The material properties of GPLs and porosity change smoothly along the thickness of the plate. Subsequently, the governing equations are solved based on Galerkin principle and the conclusions are given as,

(1) When the wave number is small, the phase velocity decreases sharply with the increase of the wave number. The values of phase velocity can be ranked in order as follows: GPL-A>GPL-C>GPL-B.

(2) When the wave number keeps unchanged, the phase velocity of shear wave is greater than longitudinal wave and bending wave.

(3) When the wave number keeps unchanged, the values of phase velocity can be ranked in order as follows: Porosity-I>Porosity-III>Porosity-II.
(4) Under a certain wave number, phase velocity decreases significantly with the increase of porosity coefficient.
(5) Under a certain wave number, the phase velocity increases significantly as the GPLs weight fraction rises.
(6) The impact of elastic foundation on shear wave can be ignored, but the influence of elastic foundation on bending wave is more significant. The larger the kw or ks, the larger the phase velocity.

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