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Harmonic Vibration of Inclined Porous Nanocomposite Beams

D. Chen and L. Zhang

Abstract This work investigated the linear harmonic vibration responses of inclined beams featured by closed-cell porous geometries where the bulk matrix materials were reinforced by graphene platelets as nanofillers. Graded and uniform porosity distributions combined with different nanofiller dispersion patterns were applied in the establishment of the constitutive relations, in order to identify their effects on beam behavior under various harmonic loading conditions. The inclined beam model comprised of multiple layers and its displacement field was constructed using Timoshenko theory. Forced vibration analysis was conducted to predict the time histories of mid-span deflections, considering varying geometrical and material characterizations. The findings may provide insights into the development of advanced inclined nanocomposite structural components under periodic excitations.

Keywords Functionally graded porosity · Graphene platelets · Harmonic vibration · Inclined beams

1 Introduction

The inclined beam problem has attracted many researchers and engineers due to its application potential in various fields (bridges and skytrain rail [1], for instance). The axial force induced by the inclined angle leads to a different deformation pattern compared with horizontal beams [2]. Meanwhile, in order to achieve enhanced performance, inclined structures with novel material compositions have been proposed, such as functionally graded (FG) inclined pipes [3] and inclined FG sandwich beams [4]. The recent development in this field using graded distributions of porosity and graphene platelets (GPLs) is demonstrated to be promising. Chen et al. [5] pointed

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out that strategic arrangements of internal pore size/density and GPL weight fractions significantly benefit the low-velocity impact properties of inclined beams under various impulses. The combination of FG porosities and graphene nanofillers can boost the mechanical performance of lightweight structural components [6, 7].

In this work, we aimed to further reveal the behavior of this novel porous nanocomposite by focusing on the responses of corresponding inclined beams under harmonic excitations, which represent steady wind, unbalanced rotating machine force, or vehicle loadings, etc. The theoretical formulations were first briefed and validated, then the mid-span deflections of fully clamped beams with changing inclined angles, porosity coefficients, GPL weight fractions and slenderness ratios were examined, considering the typical harmonic force sitting on the top mid-span surface.

2 Formulation Briefing

Figure 1 is a schematic illustration of the examined FG beam, of which the elastic properties varied along the height direction with $E(z) = E^*[1 - e_0\alpha(z)]$ for Young's modulus, $G(z) = E(z)/[2(1 + \nu(z))]$ for shear modulus, and $\rho(z) = \rho^*[1 - e^*\alpha(z)]$ for mass density, where Young's modulus of non-porous nanocomposites $E^* = \phi(E_{Al}, \Delta_{GPL})$ were determined using the Halpin–Tsai micromechanics model, e_0 reads the porosity coefficient related to internal pore size/density, $\alpha(z) = \cos(\pi z/h)$ and $\alpha(z) =$ constant correspond to the graded and uniform porosities, respectively, and $\rho(z)$ and $G(z)$ root in the closed-cell morphologies. The GPL weight fraction was $\Delta_{GPL} = \zeta_1[1 - \cos(\pi z/h)]$ for non-uniform dispersions and $\Delta_{GPL} = \zeta_2$ for the uniform one, while ζ_1 and ζ_2 were related to material distributions. The mass density and Poisson's ratio of non-porous nanocomposites were computed via the rule of the mixture with the corresponding values of the matrix materials (ρ_{Al}, ν_{Al}) and GPLs (ρ_{GPL}, ν_{GPL}). Note that the FG variations of porosity and GPL dispersion were both symmetric about the mid-height plane. Based on the established constitutive relations, the beam governing equation systems were derived within the framework of Timoshenko theory, and solved with the aid of the Ritz method and Newmark method. Consequently, the time history of beam mid-span deflections was estimated, in which the initial deformation status caused by self-weight was also embedded [5].

3 Results and Discussion

Based on aluminum composites, the parameters adopted in this study included $E_{Al} = 70$ GPa, $\rho_{Al} = 2700$ kg/m^3, $\nu_{Al} = 0.34$, $w_{GPL} = 1.5$ μm, $l_{GPL} = 2.5$ μm, $t_{GPL} = 1.5$ nm, $E_{GPL} = 1.01$ TPa, $\rho_{GPL} = 1062.5$ kg/m^3, $\nu_{GPL} = 0.186$. The beam section dimension was 0.1×0.1 m and the layer number was 14 [8]. The time length (2 s) was

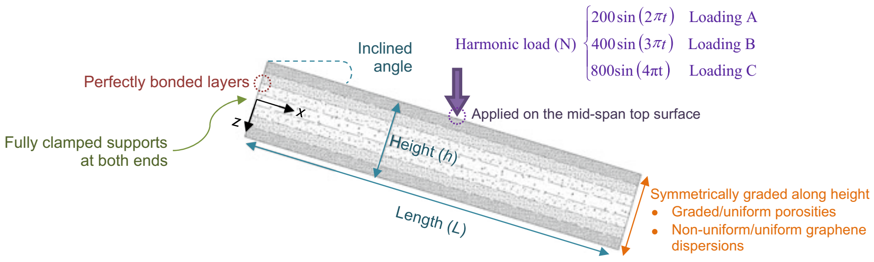
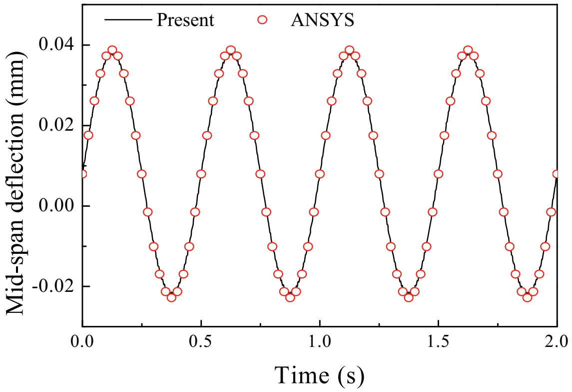


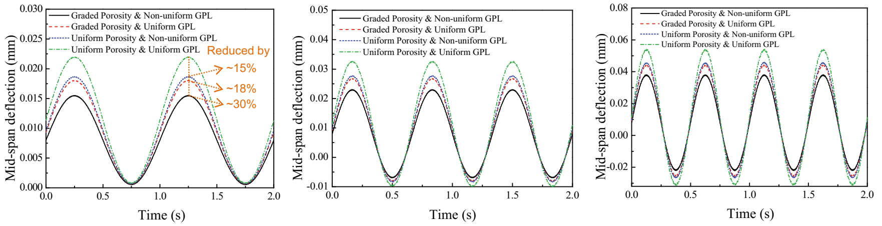
Fig. 1 Inclined functionally graded beam

the same for all calculation cases to obtain the maximum absolute value of the mid-span deflections. The beam boundary condition was taken as the clamped–clamped end supports. The present results were validated by being compared with ANSYS simulations (see Fig. 2). Figure 3 shows the mid-span deflection time histories of the examined beams under three harmonic loading scenarios. Results suggested that dispersing both internal pores and GPLs non-uniformly enhanced the inclined beam's stiffness due to reduced maximum deflections (~15%, ~18%, ~30%, as marked in Fig. 3a). It is also noticeable that the minimum deflections for the beams remained almost the same in loading case A but differed in loading cases B and C, because of the influence of gravity and the increased peak force in B and C.

For the purpose of simplification, the assessment given below is limited to responses subjected to harmonic loading case A. Figure 4a compares the harmonic vibration deflections of beams inclined at various angles. It is obvious that a larger inclined angle resulted in smaller deflections with lower harmonic force components along the height direction. The variations of porosity coefficient and GPL weight fraction are displayed in Figs. 4b, c. We can see that when the porosity coefficient increased from 0.2 to 0.6, the maximum deflection increased by ~10%. Meanwhile, an improved level of graphene weight fraction from 0.2% to 1.0% significantly

Fig. 2 Mid-span deflection time history of an inclined (45°) beam with graded porosity and non-uniform GPL dispersion under loading case C ($e_0 = 0.5$, $\Delta_{GPL} = 1.0\,wt.\%$, $L/h = 20$)



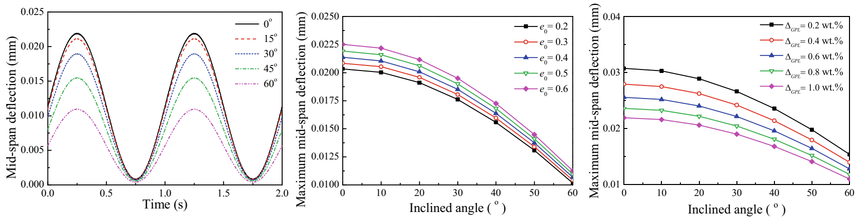


(a) Loading A **(b)** Loading B **(c)** Loading C

Fig. 3 **a–c** Mid-span deflection time histories of inclined functionally graded beams under harmonic loadings (inclined angle 45°, $e_0 = 0.5$, $\Delta_{GPL} = 1.0\,wt.\%$, $L\,/\,h = 20$)

stiffened the inclined beam of which the maximum mid-span deflection evidently decreased (~29%).

Table 1 details the influence of the slenderness ratio and inclined angle on the maximum mid-span deflections of inclined beams and still considers loading case A. Compared with two extreme cases (60° for *L/h* = 20; 0° for *L/h* = 40), a wide gap of 0.2476 mm was identified between their deflections.



(a) Inclined angle **(b)** Porosity coefficient **(c)** Graphene weight fraction

Fig. 4 **a–c** Mid-span deflections of inclined functionally graded beams under harmonic loading A (graded porosities & non-uniform graphene dispersions, $e_0 = 0.5$ and $\Delta_{GPL} = 1.0\,wt.\%$ for **a**, $\Delta_{GPL} = 1.0\,wt.\%$ for **b**, $e_0 = 0.5$ for **c**, $L/h = 20$)

Table 1 Maximum mid-span deflections (mm) of inclined beams under harmonic loading A (graded porosity & non-uniform graphene dispersion, $e_0 = 0.5$, $\Delta_{GPL} = 1.0\,wt.\%$)

Inclined angle	$L/h = 20$	$L/h = 30$	$L/h = 40$
0°	0.0219	0.0911	0.2586
20°	0.0206	0.0856	0.2430
40°	0.0168	0.0698	0.1981
60°	0.0110	0.0455	0.1293

4 Conclusions

We have discussed the influence of inclined angle, porosity, and graphene on beam harmonic vibration responses. We conclude that all three parameters are closely related to beam deflections under different harmonic loadings. The examined porous nanocomposites may be used to develop novel inclined structural components with reduced weight and enhanced stiffness subjected to periodic excitations.

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