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Nonlinear transient response of basalt/nickel FGM composite plates under blast load

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Abstract

In this study, the nonlinear dynamic response of basalt/nickel FGM composite plates has been investigated under blast load. Homogenous Laminated Model (HLM) and Power-Law Model (PLM) are used to model the basalt/nickel FGM composite plates. von Kármán large deflection theory of thin plates are considered for the geometric nonlinearity effects. The equations of motion for the plate are derived by the use of the virtual work principle. Approximate solutions are assumed for the space domain and substituted into the equations of motion. Then the Galerkin Method is used to obtain the nonlinear differential equations in the time domain. The Finite Difference method is applied to solve the system of coupled nonlinear equations. The effects of two different approximations in order to model the basalt/nickel FGM composite plates have been investigated and the results are discussed.

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*Keywords:*Basalt/nickel FGM; laminated composite; plate; simply-supported; blast load

1. Introduction

In recent years, Functionally Graded Materials (FGM) plays an important role among the advanced composite materials. Laminated composites are also widely used in many industrial applications such as aerospace structures, marine structures and automobiles. Therefore, the use of the laminated FGM composite plates has many application

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areas. The material composition of FGM varies continuously along the thickness direction of the laminates. In other words, two dissimilar materials, such as one is a ceramic and the other one is a metal, have been combined in order to form new material which has continuously changing mechanical properties along thickness direction. This is obtained by gradually varying the volume fraction of the constituent materials. Due to grading properties continuously, the disadvantages of interfaces can be eliminated.

The use of FGM was first introduced by a group of Japan Scientist in 1984 as ultrahigh temperature resistant materials [1]. Later, several numerical studies presented about FGM in the literature. Woo and Meguid [1] studied the large deflection of FGM plates and shallow shells under transverse loading and temperature field. Praveen and Reddy [2] investigated the response of FGM ceramic-metal plates using finite element method. They consider the volume fraction of the ceramic and metallic constituent using a simple power-law distribution. Bank-Sills et al. [3] modeled FGM in five different models, two of which simulate fiber phases and three simulate particle phases. They concluded that a continuously changing material model is a good candidate for carrying out dynamic analyses of FGM. Aksoylar et al. [4] analyzed the nonlinear transient dynamic behavior of fiber-metal laminated (FML) composite plates and functionally graded (FGM) thin plates under blast load with developed mixed FEM by both experimental and numerical techniques.

Moreover, several studies related to the effects of blast load on the composite plate structures are presented in the literature up to now. To name a few, Hause [5] has developed the foundation of the theory of functionally graded plates with simply supported edges, under a Friedlander explosive air-blast load. Abrate [6] examined transient response of beams, plates, and shells to impulsive loads using the modal expansion technique for pulse shapes typically observed during impacts and explosions. Baştürk et al. [7] investigated the nonlinear dynamic response of laminated basalt composite plates under dynamic loads. Kazancı and Mecitoğlu [8] investigated nonlinear damped vibrations of a laminated composite plate subjected to blast load. Chandrasekharappa and Srirangarajan [9] investigated nonlinear response of elastic plates to pulse excitations. Kazancı [10] conducted a parametric study on the nonlinear dynamic response of laminated composite sandwich plates. Kazancı and Mecitoğlu [11] studied the nonlinear vibration of a laminated composite plate subjected to blast load. Süsler et al. [12] investigated the nonlinear dynamic behavior of tapered laminated plates subjected to blast load. An analytic tool was presented for the nonlinear dynamic behavior of hybrid laminated composite plates under several dynamic loads by Şenyer and Kazancı [13]. Süsler et al. [14] investigated the nonlinear dynamic behavior of simply supported tapered sandwich plates subjected to air blast loading theoretically and numerically. Baştürk et al. [15] studied on the nonlinear dynamic response of a hybrid laminated composite plate composed of basalt, kevlar/epoxy and glass/epoxy under the blast load including damping effects.

In last few decades, there has been increasing usage in advanced composite materials for structures due to their preferable properties such as basalt. Basalt fibers reinforced composites have higher properties over the other composites such as: better impact strength and good mechanical performance, in particular at high temperature. Additionally, due to the potential low cost of basalt composites, new basalt fiber composite applications could be widely used in near future.

As can be seen from the above mentioned literature summary, although the use of basalt in the composite materials increases rapidly, there is no study about the use of basalt as ceramic material in the functionally graded material. Therefore, in this study, it is decided to use the basalt as ceramic material in the FGM due to its high strength to the temperature. In the aerospace applications, such as turbine blade nickel based super alloys are used due to their high temperature strength, toughness, and resistance to degradation in corrosive or oxidizing environments. Therefore, it is also decided to use the nickel for the metal part of the FGM. In this study, the nonlinear dynamic response of basalt/nickel FGM composite plates has been investigated under blast load. Two different approximations are taken into account to model the basalt/nickel FGM composite plates such as Homogenous Laminated Model (HLM) and Power-Law Model (PLM). von Kármán large deflection theory of thin plates are considered for the geometric nonlinearity effects. The boundary conditions are selected as all edges simply supported. The equations of motion for the plate are derived by the use of the virtual work principle. Approximate solutions are assumed for the space domain and substituted into the equations of motion. Then the Galerkin Method is used to obtain the nonlinear differential equations in the time domain. The Finite Difference Method is applied to solve the system of coupled nonlinear equations. The effects of two different approximations in order to model the basalt/nickel FGM composite plates have been investigated.

2. Modeling of FGM Plate

A laminated basalt/nickel functionally graded composite plate subjected to blast load is considered. The material properties of basalt and nickel is described in Table 1 and the rectangular plate with the length a=0.22 m, the width b=0.22 m, and the thickness h=0.005m, is depicted in Fig. 1. The Cartesian axes are used in the derivation.

In this study, the FGM plate has been modeled in two different ways such as Homogenous Laminated Model (HLM) and Power-Law Model (PLM). In all cases, the thickness of the plate is divided into a finite number of layers and the equivalent effective material properties of these layers are defined. It is selected to divide the FGM plate to 20 in all cases as seen in Fig. 1.

Table 1.Material properties of basalt and nickel.

Material	Modulus of Elasticity (GPa) (E_1=E_2)	Shear Modulus G_{12} (GPa)	Poisson's Ratio ν	Density ρ (kg/m^3)
Basalt	25	4	0.086	2800
Nickel	200	80	0.322	8900

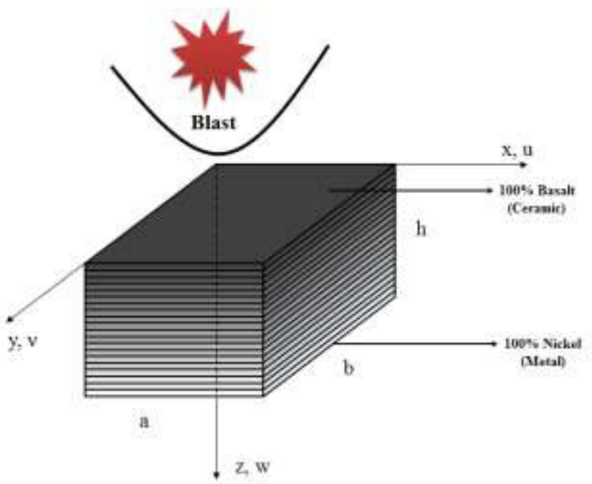

Fig. 1. Homogenous Laminated basalt/nickel FGM composite plate (20 layers).

2.1. Homogenous Laminated Model (HLM)

In this approach (as described in [3]), the plate is divided into 20 layers. The ceramic volume fraction (Vc) of the upper layer is 1 which means fully ceramic (for this study basalt), and the ceramic volume fraction of the lower layer is 0 which means fully metal (for this study nickel). In all cases, $V_c + V_m = 1$ should be obtained. "c" denotes ceramic, basalt in this case, and "m" denotes metal, nickel in this case. The other layers have the linear change in the ceramic volume fraction from 1 to 0. The material properties are calculated from Eq.(1).

$$\mathbf{P(z)} = (\mathbf{P_c} - \mathbf{P_m}).\mathbf{V_c} + \mathbf{P_m} \tag{1}$$

All material properties such as Young's Modulus (E), Shear Modulus (G), Poisson's ratio (ν) and density (ρ) could be able to calculate from Eq.(1).

2.2. Power-Law Model (PLM)

The material properties vary non-symmetrically through the thickness for Power-Law Model. This model is defined in [1,2] as following:

$$\mathbf{V_c(z)} = \left(\frac{\mathbf{2z+h}}{\mathbf{2h}}\right)^{\mathbf{n}} \tag{2}$$

$$\mathbf{P(z)} = (\mathbf{P_c} - \mathbf{P_m}).\mathbf{V_c} + \mathbf{P_m} \tag{3}$$

The thickness of the plate is divided into a finite number of homogenous layers and the equivalent effective material properties of these layers are defined as the average value of Eq.(3) within the layer:

$$\mathbf{P_{eq}^k} = \int_{\mathbf{zb_k}}^{\mathbf{zt^k}} \frac{\mathbf{P(z)}}{\mathbf{h_k}} \mathbf{dz}, \; \mathbf{k} = \mathbf{1, 2, \ldots L} \tag{4}$$

where L is the total number of layers that is used for modeling the equivalent laminates corresponding to the FGM material.

3. Equations of motion

A laminated basalt composite plate subjected to blast load is considered. The rectangular plate with the length a, the width b, and the thickness h, is depicted in Fig. 1. The Cartesian axes are used in the derivation.

Using the constitutive equations and the strain-displacement relations in the virtual work and applying the variational principles, nonlinear dynamic equations of a laminated composite plate can be obtained in terms of mid-plane displacements as follows

$$\begin{aligned}
&L_{11}u^0 + L_{12}v^0 + L_{13}w^0 + N_1(w^0) + \bar{m}\ddot{u}^0 - q_x = 0\\
&L_{21}u^0 + L_{22}v^0 + L_{23}w^0 + N_2(w^0) + \bar{m}\ddot{v}^0 - q_y = 0\\
&L_{31}u^0 + L_{32}v^0 + L_{33}w^0 + N_3(u^0, v^0, w^0) + \bar{m}\ddot{w}^0 - q_z = 0
\end{aligned} \tag{5}$$

where L_{ij} and N_i denote linear and nonlinear operators, respectively. $\bar{m}$ is the mass of unit area of the mid-plane, q_x, q_y and q_z are the load vectors in the axes directions. The explicit expressions of the operators can be found in Kazancı and Mecitoğlu [11].

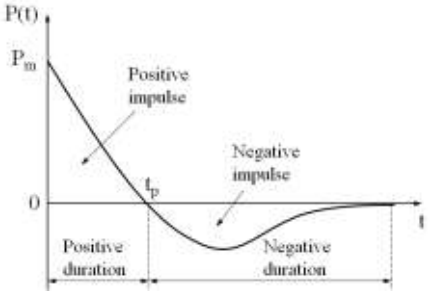

Fig. 2. Exponential blast loading.

If the blast source is distant enough from the plate, exponential air blast load can be described in a functional form such as the Friedlander equation (Gupta et al. [16]) as

$$P(t) = P_m(1 - t/t_p)e^{-\alpha t/t_p} \quad (6)$$

where the negative phase of the blast is included. In this equation, P_m is the peak blast pressure, t_p is positive phase duration, and α is waveform parameter (see Figure 2).

4. Numerical Results

First of all, the structural model for Homogenus Laminated Model was validated with ANSYS finite element software results. The maximum blast pressure$\mathbf{P_m}$ in Eq.(6) is taken to be 1000 kPa for the plate and all edges are simply supported. The other parameters of the Friedlander function given in Eq.(6) are chosen as α= 0.35 and t_p=0.0018 s. The displacement-time histories of the plate center obtained by using finite difference solution method and compared with ANSYS results in Figure 3. However, there is a discrepancy after the strong blast (first peak) effect, which is caused by the one term approximation functions used in the approximate-numerical methods as mentioned in [11].

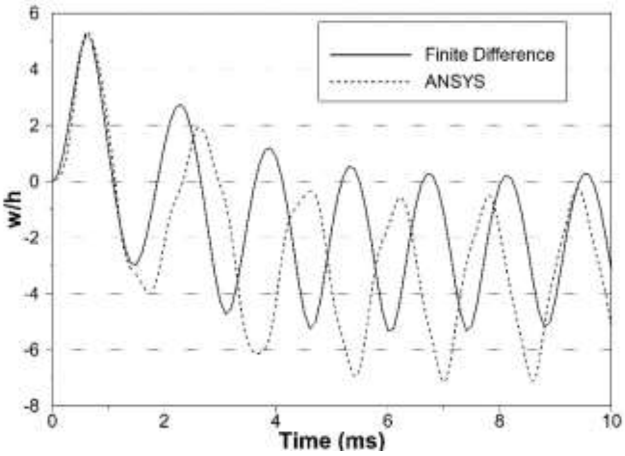

Fig. 3. Comparison of the different methods.

After this validation, the dynamic responses of basalt/nickel composites under blast load are compared for different approximations as described above such as HLM and PLM. The structure is divided into 20 layers as described above. Table 2 gives all material properties of the 20 layers for HLM while Table 3 is for PLM for n=1.0.

Table 2.Ceramic (Basalt) Volume Fractions and other material properties for HLM.

n^{th} Layer	Ceramic (Basalt) Volume Fraction V_C%	Modulus of Elasticity (GPa) (E_1=E_2)	Shear Modulus G_{12} (GPa)	Poisson's Ratio ν	Density ρ (kg/m^3)
1	100.00	25	4	0.09	2800.00
2	94.74	34	8	0.10	3121.05
3	89.47	43	12	0.11	3442.11
4	84.21	53	16	0.12	3763.16
5	78.95	62	20	0.14	4084.21
6	73.68	71	24	0.15	4405.26
7	68.42	80	28	0.16	4726.32
8	63.16	89	32	0.17	5047.37
9	57.89	99	36	0.19	5368.42
10	52.63	108	40	0.20	5689.47
11	47.37	117	44	0.21	6010.53
12	42.11	126	48	0.22	6331.58
13	36.84	136	52	0.24	6652.63
14	31.58	145	56	0.25	6973.68
15	26.32	154	60	0.26	7294.74
16	21.05	163	64	0.27	7615.79
17	15.79	172	68	0.28	7936.84
18	10.53	182	72	0.30	8257.90
19	5.26	191	76	0.31	8578.95
20	0.00	200	80	0.32	8900.00

Table 3.Ceramic (Basalt) Volume Fractions and other material properties for PLM (n=1).

n^{th} Layer	Ceramic (Basalt) Volume Fraction V_C%	Modulus of Elasticity (GPa) (E_1=E_2)	Shear Modulus G_{12} (GPa)	Poisson's Ratio ν	Density ρ (kg/m^3)
1	100	25	4	0.09	2800
2	92.5	38.12	9.7	0.10	3257
3	87.5	46.87	13.5	0.11	3562
4	82.5	55.62	17.3	0.12	3867
5	77.5	64.37	21.1	0.14	4172
6	72.5	73.12	24.9	0.15	4477
7	67.5	81.87	28.7	0.16	4782
8	62.5	90.62	32.5	0.17	5087
9	57.5	99.37	36.3	0.19	5392
10	52.5	108.12	40.1	0.20	5697
11	47.5	116.87	43.9	0.21	6002
12	42.5	125.62	47.7.	0.22	6307
13	37.5	134.37	51.5	0.23	6612
14	32.5	143.12	55.3	0.25	6917
15	27.5	151.87	59.1	0.26	7222
16	22.5	160.62	62.9	0.27	7527
17	17.5	169.37	66.7	0.28	7832
18	12.5	178.12	70.5	0.29	8137
19	7.5	186.87	74.3	0.30.	8442
20	0	200	80	0.32	8900

Figure 4 shows the displacement time histories of the mid plane of the structure for P_m=1000 kPa. If n value, in Eq.(2) is taken as 1.0, the time histories for HLM and PLM should be the same, as can be seen from the Figure 4.

Figure 5 shows the effect of different n values for PLM approximation. n values are taken as 0.5, 1.0, 2.0, and 5.0. It can be said that the maximum deflection can be obtained for n=0.5 and the minimum deflection can be obtained for n=5.0. Also, the frequency increases while n value decreases.

Figure 6 shows the displacement time histories for the various aspect ratios of the basalt/nickel FGM composite plate. The mid-plane area of the plate is preserved as a constant value for all the aspect ratios. The peak deflection of the plate decreases while the aspect ratio decreases. However, it can be seen that, the vibration frequency increases with the decreasing aspect ratio.

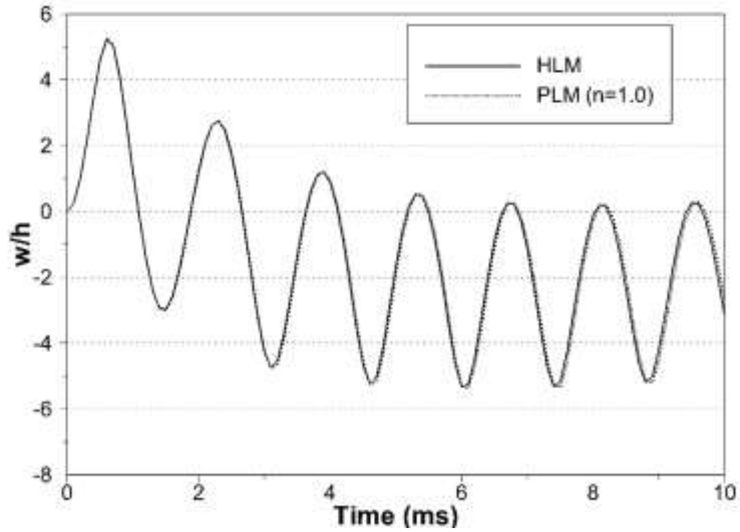

Fig. 4. Comparison of HLM and PLM for n=1.0.

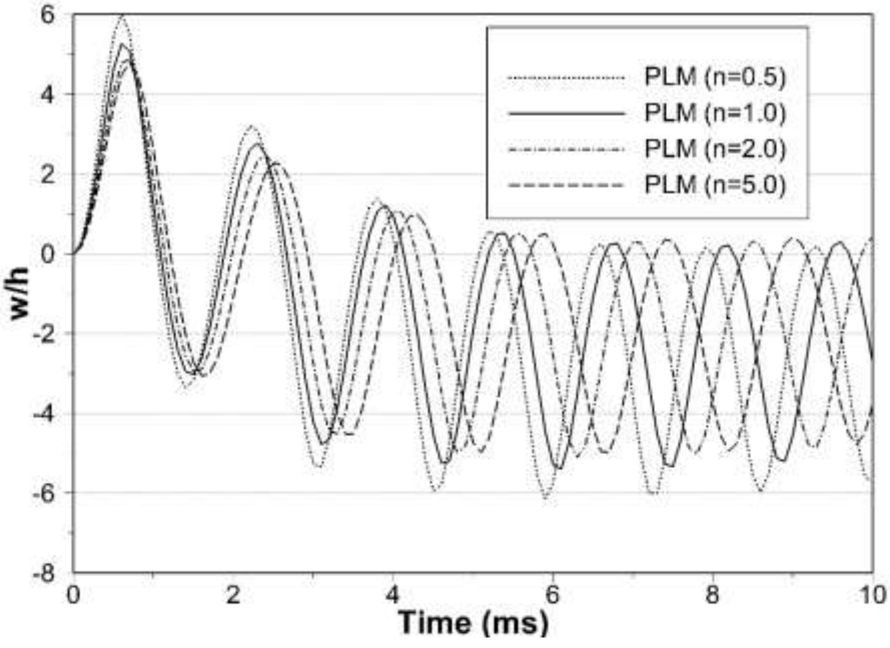

Fig. 5. Effect of different n values for PLM.

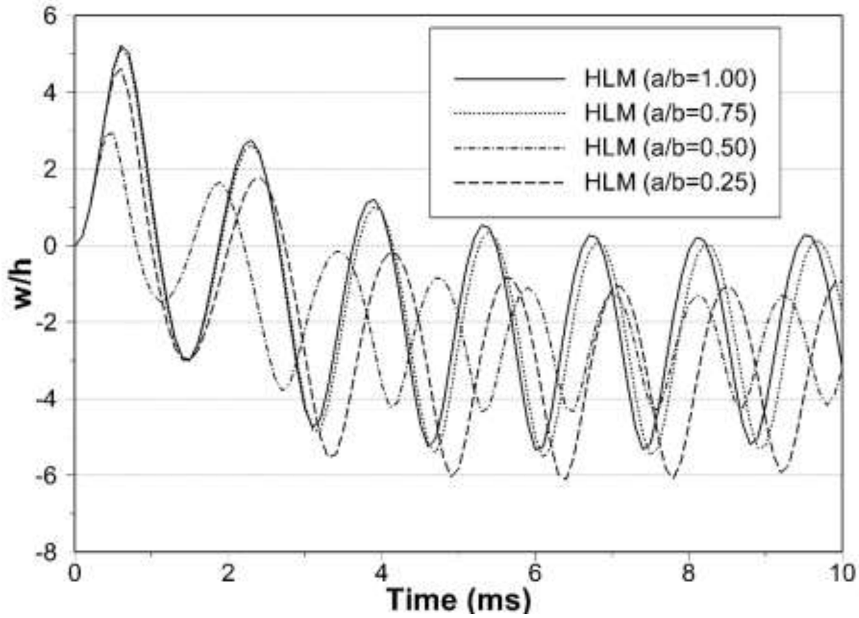

Fig. 6. Comparison of different aspect ratios.

5. Conclusions

In this study, the nonlinear dynamic response of basalt/nickel FGM composite plates has been investigated under blast load. Two different approximations are taken into account to model the basalt/nickel FGM composite plates such as Homogenous Laminated Model (HLM) and Power-Law Model (PLM). von Kármán large deflection theory of thin plates are considered for the geometric nonlinearity effects. The boundary conditions are selected as all edges simply supported. The equations of motion for the plate are derived by the use of the virtual work principle. Approximate solutions are assumed for the space domain and substituted into the equations of motion. Then the Galerkin Method is used to obtain the nonlinear differential equations in the time domain. The Finite Difference Method is applied to solve the system of coupled nonlinear equations. The effects of two different approximations in order to model the basalt/nickel FGM composite plates have been investigated and the results are discussed.

It can be concluded that the results of HLM and PLM approach is same for n=1.0 while the maximum deflection can be obtained for n=0.5 and the minimum deflection can be obtained for n=5.0. The vibration frequency is increasing while n value decreases. A parametric study is conducted for the basalt/nickel FGM composite plate subjected to blast load considering the effects of aspect ratio. While the aspect ratio of the plate decreases, the amplitude of the plate decreases, and the corresponding frequency increases.

For the future studies, different blast load types, different material properties, damping effects and other boundary conditions could be taken into account.

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