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An analytical model for predicting the deflection of laminated basalt composite plates under dynamic loads

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ABSTRACT

The nonlinear dynamic response of laminated basalt composite plates has been investigated under dynamic loads. The geometric nonlinearity effects are taken into account with the von Kármán large deflection theory of thin plates. All edges simply supported boundary conditions are considered. 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 and Newmark methods are applied to solve the system of coupled nonlinear equations. The effects of different loading conditions on the laminated basalt composites have been investigated. A parametric study is conducted considering the effects of aspect ratio, fiber orientation, peak pressure values, thickness, and waveform parameter. The objective is to show that, the laminated basalt composites would be a good alternative for structures under dynamic loads.

1. Introduction

Advanced laminated composites are important structural components that are widely used in various engineering applications such as space station structures, aircrafts, automobiles and marine structures. With the advent of the new composite material structures and their increased use in military industry, the problem of nonlinear dynamic behavior of laminated composite plates exposed to time-dependent pulses, such as blast loads occurring from fuel and nuclear explosions, gust and sonic boom pulses becomes more important.

For years now, several studies related to the effects of time-dependent external pulses (such as blast load) on the plate structures are reported in the literature. To name a few, Rajendran and Lee [1] reviewed the phenomenological evolution of blast loaded plates. They summarized the phenomena of air and underwater explosions and their effects on plane plates. Abrate [2] 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. Birman and Bert [3] considered the response of simply supported laminated plates subjected to explosive blast loading. Dobyns [4] investigated static and dynamic analysis of orthotropic plates considering transient loading conditions. Kazancı and Mecitoğlu [5] studied nonlinear damped vibrations of a laminated composite plate subjected to blast load. Chandrasekharappa and Srirangarajan [6] investigated nonlinear response of elastic plates to pulse excitations. The results of dynamic analyses were carried out on both stiffened and unstiffened panels subjected to blast loading using both simplified and advanced analytical techniques by Louca and Pan [7]. Kazancı [8] conducted a parametric study on the nonlinear dynamic response of laminated composite sandwich plates. Türkmen and Mecitoğlu [9,10] studied nonlinear dynamic response of laminated and stiffened laminated composite plates subjected to blast load theoretically and experimentally. Kazancı and Mecitoğlu [11] studied the nonlinear vibration of a laminated composite plate subjected to blast load based on the von Kármán large deflection theory of thin plates. 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]. Yazici et al. [14] have developed a sandwich structure with improved performance under blast load at room temperatures. For simulating the explosive blast load, a dynamic loading method was developed by Chen et al. [15] using a crushing foam projectile launched by a gas gun. Jang and Choi [16] have employed a new approach, using integrated material and a product

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design to obtain a blast resistant panel. Aksoylar et al. [17] have studied the nonlinear transient behavior of fiber–metal laminated (FML) composite plates under non-ideal blast loads.

In last few decades, there has been increasing usage in advanced composite materials for structures due to their preferable properties. One of the recent promising material for the fabrication of the advanced composite materials is basalt fiber. Basalt is a natural inert material produced naturally from the volcanic rocks [18]. Composites reinforced with basalt fibers have prominent properties over the other composites. Some of these properties are: 17.5% better elastic modulus than fiberglass, considered as "green" recyclable, non-respirable and safer even in the factory, no UV treatments are needed, do not harbor mold or mildew or bacteria, ten times better electrical insulator than fibreglasses, high temperature strength, will not ignite easily with the right resins and low cost. Basalt composites also have better impact strength. Basalt does not shatter like carbon fibers and is a great blast resistant fiber. They also protect from nuclear radiation and does not conduct electricity or interfere with RF signals or MRI waves. Although basalt fibers have good mechanical performance, in particular at high temperature, its possible applications has not been investigated completely yet. New basalt fibre composite applications could be widely used in near future due to the potential low cost of this material. Lopresto et al. [19] have investigated the mechanical characterization of basalt fiber reinforced plastic. They found that basalt composite showed 35–42% higher Young's modulus as well as better compressive strength and flexural behavior, while a higher tensile strength was found for glass fibers. Manikandan et al. [20] have been investigated the effect of surface modifications with NaOH and H_2SO_4 on mechanical properties including tensile, shear and impact strengths. The results showed that the mechanical properties of basalt fibre reinforced composites are superior to glass fibre reinforced composites. They confirm the use of basalt fibre as a reinforcing agent in polymer composites. Lee et al. [21] have investigated the effect of carbon nanotube (CNT) modification on the tensile and thermal properties of CNT/basalt/epoxy composites. Particularly they found that the tensile strength and Young's modulus of silanized composites were 34% and 60% greater, respectively, than that of unmodified composites. Zhang et al. [22] are fabricated basalt fiber reinforced poly (butylene succinate) composites and investigated the effects of the basalt fiber on the mechanical and thermal properties of the composites. The results showed that using of basalt fibers as reinforcement in a natural fiber composite can significantly improve the mechanical properties and performance of polymer matrix resins. Eslami-Farsani et al. [23] have been studied on the tensile properties of clay reinforced polypropylene nanocomposites and chopped basalt fiber reinforced polypropylene–clay nanocomposites. They have concluded that the nanoclay particles can be added into the fiber reinforced composites in order to improve the mechanical properties such as Young's modulus and yield strength as a filler or third phase additive. Elsanadedy et al. [24] used a new type basalt-based textile in order to strength the material. Colombo et al. [25] have described the experimental results of several static and fatigue tests of the new basalt fibre reinforced composites.

There are also several studies on the low velocity impact behaviors of the basalt composites. To name a few, Wang et al. [26] have tested the low velocity impact properties of 3D woven basalt/aramid hybrid composites. Tehrani et al. [27] have investigated the low velocity impact behavior of homogenous and hybrid composite laminates reinforced by basalt–nylon intra-ply fabrics. They showed that the impact performance of these composites is significantly affected by the nylon/basalt fibers ratio. By increasing the nylon/basalt fibers ratio, the most important failure character changes, from fiber breakage to extended delamination. Sarasini et al. [28] have studied impact damage modes and residual flexural properties of hybrid composites based on aramid and basalt woven fabrics. It has been seen from the results that hybrid composites with alternating sequence of basalt and aramid have better impact energy absorption capability and enhanced damage tolerance with respect to the all-aramid laminates. They also showed that the most favorable flexural behavior has been obtained from basalt and hybrid laminates with sandwich-like configuration. Sarasini et al. [29] have also studied on drop-weight impact behavior of woven hybrid basalt–carbon/epoxy composites at their other research. The results showed that hybrid laminates with intercalated configuration have better impact energy absorption capability and enhanced damage tolerance with respect to the all-carbon laminates.

As can be seen above, a lot of works have been done on mechanical, thermal and low velocity impact behavior of basalt composite plates. However, according to the study in the literature, no article was found to investigate the nonlinear dynamic behavior of basalt composites subjected to blast load. There are two possible effects of the blast [30]: sudden pressure and the temperature rise. Therefore, using the basalt composites subjected to blast loads would be preferable due to their high temperature resistance. Therefore, the objective of the present paper is to investigate the nonlinear dynamic behavior of simply supported laminated basalt composites subjected to dynamic loads especially for blast.

In this paper, the dynamic behaviors of the laminated basalt composite plates exposed to time-dependent lateral loads have been investigated. The geometric nonlinearity effects are taken into account with the von Kármán large deflection theory of thin plates. The equations of motion for the plate are derived by the use of the virtual work principle. Approximate displacement functions are assumed for the space domain by considering the nonlinear static deformations obtained using ANSYS software. They are substituted into the equations of motion and then the Galerkin Method is used to obtain the nonlinear differential equations in the time domain. The finite difference method and Newmark method are applied to solve the system of coupled nonlinear equations and a program code in FORTRAN software is written for use in calculation. A parametric study is conducted considering the effects of aspect ratio, fiber orientation, peak pressure values, thickness, and waveform parameter. The results of approximate-numerical analyses are obtained and detailed discussions are made about the displacement–time histories. The objective of this study is to show that, in such loading cases, using basalt fiber composite plates may well be more preferable or might at least provide a valuable alternative for composite structures.

2. 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.

The displacement functions of a thin plate can be expanded in the series. If the first few terms in the series are taken, the displacement functions can be approximated as follows

$$u = u^0 - z\frac{\partial w^0}{\partial x} \tag{1a}$$

$$v = v^0 - z\frac{\partial w^0}{\partial y} \tag{1b}$$

$$w = w^0 \tag{1c}$$

where u, v and w are the displacement components in the x, y and z directions. $()^0$ indicates the displacement components of reference surface.