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Simulation of the dynamic response of GLARE plates subjected to low velocity impact using a linearized spring–mass model

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ABSTRACT

In this article, the low velocity impact response of circular clamped GLARE fiber-metal laminates is treated analytically using a linearized spring–mass model. Differential equations of motion which represent the physical impact phenomenon are formulated and the corresponding initial value problems are set. Then, exact symbolic solutions of these problems are derived and expressions to calculate the impact load, position, velocity and kinetic energy time histories are given. Also, analytical equations to predict the coefficient of restitution and the energy restitution coefficient of the impact event are presented. The analytical formulas are applied in order to simulate published experiments concerning normal central low velocity impact of GLARE 4 and GLARE 5 circular laminates. The analytical and experimental impact load time histories of the two GLARE plates are found in good agreement. Apart from circular clamped GLARE plates, the equations of this article can also be employed in order to approximate the response of other GLARE or hybrid composite structures, when subjected to similar low velocity impact damage phenomena.

1. Introduction

Fiber-metal laminates are hybrid composite materials, consisting of alternating metal layers bonded to fiber-reinforced prepreg layers. ARALL (Aramid Reinforced ALuminum Laminates), CARALL (CArbon Reinforced ALuminum Laminates) and GLARE (GLAss REinforced) belong to this new family of materials. Apart from aluminum, other metal constituents such as steel, magnesium and titanium have been employed in order to manufacture fiber-metal laminates [1–4]. The possible variations of hybrid laminated material systems are numerous and their mechanical evaluation is a challenging intensive field of scientific research.

GLARE is the most successful fiber-metal laminate up to now and is currently being used for the construction of primary aerospace structures, such as the fuselage of the Airbus A380 air plane. Further applications have also been considered: aircraft cargo floors of Boeing 777, aircraft engine cowlings, bonded GLARE patch repair, aircraft stiffeners with a wide variety of shapes, cargo containers, seamless GLARE tubes [1–4].

Impact properties are very important in aerospace structures, since impact damage is caused by various sources, such as maintenance damage from dropped tools, collision between service cars or cargo and the structure, bird strikes and hail [3,5–8]. Much work has been published on the subject of impact, concerning conventional composite materials and GLARE fiber-metal laminates, which are frequently used in aerospace structures. Analytical, numerical and experimental impact studies have been considered [9–31]. In these impact studies, the static indentation, the low and high velocity impact, and the ballistic impact response of conventional and hybrid composite materials, like GLARE, are analyzed. Analysis concerning the issues of damage, failure criteria and delamination is closely related to the impact response of composite structures. A detailed analysis including also these topics can be found in reference [32], along with a discussion concerning the pertinent commercial code GENOA (General Optimization Analyzer).

This article presents a theoretical model to predict the response of thin circular clamped GLARE plates, subjected to central normal low velocity impact by a hemispherical impactor. Low velocity impacts represent damage from service trucks, cargo containers and dropped tools during maintenance [5]. A typical test method, employed by researchers in order to study the low velocity impact behavior of hybrid composites such as GLARE, is to apply central normal impact loads on circular clamped plates using a drop weight impact tester, equipped with a hemispherical impactor [4,5,9–12]. Consequently, predicting the response of circular GLARE plates to low velocity impacts has great practical importance.

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In the study of Guocai et al. [9], the above problem was investigated experimentally. Hoo Fatt et al. [13] employed a spring–mass model to predict the ballistic response of clamped square GLARE panels. They also calculated the corresponding first failure load due to glass-epoxy tensile fracture. In two articles by Tsamasphyros and Bikakis, the differential equations of motion, corresponding to the impact of a hemispherical impactor striking on a circular clamped GLARE plate, were derived using a spring–mass model as well [14] and solved [15]. Caprino et al. [18] developed a mechanistic model to predict the response of square fibreglass-aluminum laminates under low velocity impact, which requires the implementation of several experimental tests. In the work of Davar et al. [27] an assessment of different higher order shell theories for low velocity impact response analysis of simply supported fiber-metal laminate circular cylindrical shells is implemented. A spring–mass model with two degrees of freedom is employed there to predict the contact force time history. Pertinent contact laws are also discussed in the same article. Payeganeh et al. [19] studied the response of simply supported rectangular fiber-metal laminated plates subjected to low velocity impact. They employed the first-order shear deformation theory and the Fourier series method in order to solve the governing equations corresponding to a spring–mass model analytically. The Choi's linearized Hertzian contact model was used in their impact analysis [21].

The solution presented in [15] corresponds to a nonlinear oscillator. The behavior of this oscillator is described with nonlinear second order Duffing differential equations of motion. But since the Duffing equations do not have an exact symbolic solution, it was not possible to derive in [15] analytical expressions of the variations of impact variables, such as the impact load and velocity, as a function of impact time. Furthermore, this fact increases the difficulty of understanding how the input variables, such as the initial kinetic energy, affect the time history response of a GLARE plate when subjected to low velocity impact. Another disadvantage is that using the solution of reference [15], a series of tedious numerical integrations must be carried out in order to obtain the time history of each specific impact variable.

In this work, the low velocity impact problem is treated using a linearized spring–mass system. In reference [33] this approach is implemented in order to calculate an approximate value of the impact duration of conventional composite materials. The principal objective of this article is the derivation of analytical equations to predict the time histories of characteristic impact variables of the examined problem. With the solution presented in the following sections, all disadvantages described in the previous paragraph concerning the work of reference [15], are no longer valid. Also, the equations of the new solution are less complicated, a fact that further reduces the required computational effort in order to obtain the desired time histories of the impact variables.

2. Problem definition

We consider a thin clamped circular GLARE plate with radius α and thickness h as shown in Fig. 1. The plate is struck at its center by an impactor with large mass M_0 and initial low velocity U_o (the contact load duration is much higher than the lateral transit time required for the transverse shear waves to reach the plate's boundary from the point of impact [16]). We do not consider a small mass impact because testing of impact resistance of composite laminates is conventionally implemented using small specimens with large mass impactors [25]. Consequently, our analytical modeling is not valid for small mass impacts, which occur when the mass of the impactor is less than 1/4 of the mass of the largest possible area for which waves do not interfere with the boundaries of the plate [24,25]. The impactor has a hemispherical tip with radius R. The plate consists of alternating layers of aluminum and glass-epoxy. The aspect ratio α/h is assumed high, so that shear deformation and local indentation are negligible.

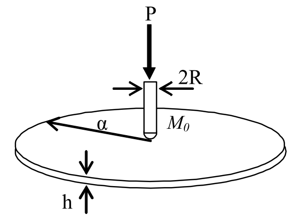

Fig. 1. Circular plate problem geometry.

The plate is clamped along its boundary. As the impactor progresses, the load P due to the global deflection of the plate and the corresponding central plate deflection w increase, while the velocity of the impactor decreases, until the plate reaches its maximum deformation. At this point, due to the elastic strain energy of the prepreg layers, which have been stretched during the loading stage, the plate starts to move toward the opposite direction, until the impact load P becomes equal to zero.

A linearized spring–mass model will be used in order to simulate the low velocity impact in three stages. During the first stage, the impactor starts to deform the plate until internal damage due to delamination occurs. The second stage starts after delamination up to the position of maximum plate deformation, while the final stage starts from this position and ends when the impact load becomes equal to zero. The corresponding linear second order differential equations of motion are formulated in order to represent this impact phenomenon. Exact symbolic solutions of these equations are given and fully analytical expressions to calculate the (w, t), $(\dot{w}, t)$, (P, t), (E_k, t) and (E_a, t) time histories are derived, where E_k is the impactor's kinetic energy and E_a is the absorbed impact energy. Using these expressions, the coefficient of restitution and the energy restitution coefficient are also determined analytically.

The assumptions made in [14], for the derivation of the corresponding nonlinear second order Duffing equations of motion are considered valid. A basic assumption, analyzed in reference [14], is that the initial kinetic energy of the impactor is high enough to cause large deflections to the GLARE plate, but it is not above the energy level that causes first failure of the glass-epoxy layers due to tensile fracture. A conservative upper initial kinetic energy limit of the impactor, in order to avoid first failure of the glass-epoxy layers due to tensile fracture, can be calculated as indicated in [14]. As also mentioned in [14], it is considered that E_k is consumed to deform the GLARE plate and cause delamination damage among glass-epoxy layers, provided that E_k is high enough to result in the application of the minimum required delamination load to the GLARE plate.

3. Governing differential equations

In reference [34] the nonlinear stiffness of a GLARE plate subjected to low velocity impact was replaced by a linear spring in order to calculate approximate values of the impact duration, as also described in reference [33] for conventional composites. During the loading stage the linearized stiffness is:

$$K_L = \frac{\Delta P_L}{\Delta w_L} = \frac{P_{\max}}{w_{\max}} \qquad (1)$$

where $P_{\max}$ and $w_{\max}$ are the maximum impact load and deflection calculated using the pertinent analytical equations of reference [34]. The spring force is then given by:

$$P_L = K_L w \qquad (2)$$

The corresponding impactor's and plate's differential equation of motion is formulated as follows: