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Large deformation dynamic finite element analysis of delaminated composite plates using contact–impact conditions

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ABSTRACT

A new C^0 composite plate finite element based on Reddy's third order theory is used for large deformation dynamic analysis of delaminated composite plates. The inter-laminar contact is modeled with an augmented Lagrangian approach. Numerical results show that the widely used "unconditionally stable" β-Newmark method presents instability problems in the transient simulation of delaminated composite plate structures with large deformation. To overcome this instability issue, an energy and momentum conserving composite implicit time integration scheme presented by Bathe and Baig is used. It is found that a proper selection of the penalty parameter is very crucial in the contact simulation.

1. Introduction

Composite structures are extremely useful for aerospace, automotive, marine and civil applications due to their very high specific structural properties. However, structures made of composite materials possess complicated failure mechanism as compared to those made from conventional metallic materials. One of the common failure modes is inter- or intra-delamination, which can be caused by pre-existing imperfections or can occur during the structures service life due to high interlaminar stresses or low/high velocity impact. Sensitive aerospace applications can have small design margins and any lacuna in knowledge of the system may precipitate design failure [1]. In composite structural design, it is very important to properly model geometrical intricacies and various imperfections such as delaminations and cracks. For accurate prediction of structural response, a mathematically sound and accurate model is always needed [2,3]. Accuracy in structural response characterization is also necessary for model based structural health monitoring. Inaccuracies in the mathematical model can lead to erroneous fault predictions [4].

There has been voluminous and intensive research in the area of delamination modeling in laminated composite structures. Most researchers have concentrated on prediction of delamination growth and the associated reduction in compressive strength of the composite structure [5]. While, some of the earlier studies have investigated the stress and deformation fields around the delamination front, others have studied the effect of delamination on flexural stiffness of beams and plates in static bending [6,7]. A detailed review on the topic of dynamics of delaminated beams is given by Luo and Hanagud [8]. Mujumdar and Suryanarayan [9] proposed a mathematical model for delamination with constraints for sub-laminates to have identical transverse deformation. Tracy and Pardoen [10] used this constrained model to study the effect of delamination on the natural frequencies of composite laminated beams. However, the constrained model lacks in physical rigor and excludes the possible breathing phenomena of sub-laminates during vibration. On the other hand, the free model presented by Wang et al. [11] where the sub-laminates are free to vibrate independently, results in interpenetration of the sub-laminates. Hu et al. [12] studied the vibration analysis of delaminated composite beams and plates using higher order finite element. Their model incorporates the displacement continuity condition at the delamination front but this model also does not restrict the sub-laminar interpenetration. They also used their model for delamination localization using curvature of vibration mode. Some of the studies address effects of delamination on dynamic characteristics of composite plates [13,14]. While most of these studies on delamination are either on strength reduction or on modal characterization of the delaminated structure, some researchers have also studied the effects of delamination on their buckling behavior [15,16].

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The effects of delamination on the dynamic response of a structure are subtler, compared to the large reductions in compressive strength [5], and there are fewer models describing these effects. The dynamic response of composite laminates with delamination is studied by some researchers [17–21]. Chattopadhyay et al. [19] carried out nonlinear vibration analysis of smart composite structures with discrete delamination using a refined layerwise theory. In their model, the contact problem of delaminated interfacial surfaces was modeled in terms of fictitious linear springs for describing the transient behavior. Although, they were able to achieve the condition of non-penetration of sub-laminates, their model was based on ad hoc assumption of a fictitious spring. The stiffness characterization of the fictitious spring was also not straight forward. Moreover, while they have studied the nonlinear effect due to contact and release conditions, their study does not incorporate large deformation effects. Oh et al. [20] investigated the dynamic behavior of laminated composite plates with multiple delaminations. They developed a four-node finite element based on an efficient higher-order zigzag plate theory of laminated composite plates with multiple delaminations for the prediction of frequencies, mode shape, and time response. Effectiveness of their model was demonstrated using numerical results in transient simulations. Their model worked well for contact simulations in delaminated composite plates using the popular β-Newmark approach. However, they have not addressed the issues of large deformation in delamination simulations incorporating contact–impact conditions. Dynamic finite element analysis of laminated beams with delamination cracks using contact–impact conditions was carried out by Kwon and Aygunes [21]. They had adopted the approach given by Hughes et al. [22] for correcting the velocity, acceleration and contact force values during release-to-contact condition. Now, this approach is also based on ad hoc assumption for correcting the important dynamic parameters. They were able to achieve non-penetration of interlaminates but the results they present can still be argued upon for its physical correctness, as both the top and bottom laminates experience a kind of total separation. In reality, they must collide more than once during the vibration as both of the sub-laminates are shown to be vibrating by themselves at higher frequencies than the contact occurrence. This modeling also excludes large deformation of the composite structure. A study of vibration of delaminated beams using nonlinear anti-interpenetration constraint model was conducted by Wang and Tong [23]. In their model, they evaluated contact spring stiffness by combining indentation of sub-laminates at the delaminated region using two springs connected in series. This approach can be said to be partially correct when the externally applied load just at the delamination is shared by both of the sub-laminates jointly. However, during vibration one sub-laminate can exert force or pressure on the other sub-laminate (as they cannot inter-penetrate), without any load application at the delaminated region. Hence, in this case the contact stiffness is likely to be different. Furthermore, this model also ignores any geometric nonlinearity which can arise during structural vibration involving large displacements and rotations.

Recently, Ghoshal et al. [5] conducted further study on a delaminated composite plate incorporating geometric nonlinearity during vibration. In this model, they used two approaches for contact modeling. In the first approach, their earlier fictitious spring approach for contact modeling [19] was used and as a second approach, they modeled the contact region with bi-modular rigid elements having very high penalty during contact. With this technique, they reported problems of instability in the response of delaminated plate structure in nonlinear contact. The order of geometric nonlinearity encountered with the loading they considered was also very low as the structural response for linear and nonlinear vibration were almost of the same magnitude. However, they achieved non-interpenetration of sub-laminates, though their algorithm suffered from instabilities even with very low order of geometric nonlinearity.

In nonlinear dynamic analysis using implicit time integration schemes, new tangent matrices are computed at the beginning of each time step and thus the solution is marched forward. However, it was soon recognized by Bathe [24] that establishing a tight dynamic equilibrium at the discrete time steps by iterations can be very important. In spite of maintaining the equilibrium with repeated iterations, the unconditionally stable trapezoidal scheme can become unstable if simulations are carried over relatively long time intervals. This instability usually manifests itself in that the response grows, and energy and momentum are not conserved [24].

Although, a vast literature exists on the effects of delamination on the dynamic response of composite structures, they have mostly ignored large deformation effects. The mathematical models presented by different researchers are based on some ad hoc assumptions and hence are not physically rigorous. The prevalent approach for applying different constraint conditions is the Lagrange multiplier method. However, this method has a problem of zero diagonal [25,26]. Augmented Lagrangian method is a method which combines the advantages of the Lagrangian multiplier approach and the famous penalty method [27]. In this paper, we use augmented Lagrangian formulation for the contact simulation. An earlier developed C^0 plate finite element model based on Reddy's third order shear deformation theory and assumed strain interpolation [28] is used for large deformation dynamic analysis of delaminated composite plates. It is also shown in this paper that the popular implicit β-Newmark method fails to properly capture the contact–impact phenomena and diverges in the large deformation contact simulation, which requires very small time steps for numerical time integration. To overcome this limitation, a composite implicit time integration scheme proposed by Bathe and Baig [29] is adopted for the nonlinear transient simulation of delaminated composite plates.

2. Finite element model

In this paper, reference configuration or total Lagrangian formulation is used for the development of the nonlinear finite element model. Fig. 1 shows the schematic of a delaminated composite plate. The displacement field for the composite plate using Reddy's third order shear deformation plate theory [1] and warping functions is given as

$$\begin{aligned} u &= u_0 + z\left[\psi_x - \frac{4z^2}{3h^2}\phi_x\right] \\ v &= v_0 + z\left[\psi_y - \frac{4z^2}{3h^2}\phi_y\right] \\ w &= w_0 \end{aligned} \tag{1}$$

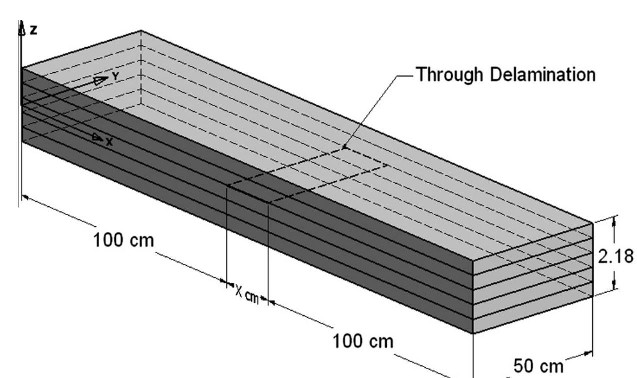

Fig. 1. Schematic of a delaminated composite plate showing through delamination of *x* cm length.