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Dynamic interaction effects of multiple delaminations in plates subject to cylindrical bending

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A B S T R A C T

The interaction of multiple delaminations in a laminated composite plate loaded dynamically under plane strain conditions (cylindrical bending) is studied by a simple but accurate model that represents the delaminated plate as a set of Timoshenko beams joined by cohesive interfaces. Behavioral maps are derived, which distinguish conditions under which multiple delaminations tend to propagate with equal lengths from those under which one of them tends to grow as a dominant crack with relatively high velocity. In homogeneous systems, equal length growth is favored when the delaminations are equally spaced through the thickness. While the behavioral maps are similar to those for static loading conditions, significant dynamic effects arise in the details of propagation: the maximum energy release rate depends strongly on the loading rate, duration and profile; dynamic effects and crack-interaction effects are generally coupled; and strong hammering effects (chaotic collisions of sub-laminates) can occur during the free wave motions that arise after the load is removed. The hammering effect can be suppressed by imposing a large-scale bridging mechanism (bridging extending far in the crack wake, as from pins or stitches), whereupon energy release rates tend to show smooth oscillations associated with waves propagating on the scale of the whole specimen. The energy absorbed during failure will depend significantly on whether conditions favor multiple delaminations propagating with equal lengths or a single delamination growing dominantly.

1. Introduction

Multiple delamination and interfacial fracture are dominant damage mechanisms of laminated and multilayered systems subject to dynamic loadings, e.g., of low and high velocity impact and blast. They are also important energy dissipation mechanisms. Often the delaminations are undetectable on the surface and may significantly reduce the stiffness of the structure and its ability to sustain repeated loadings; or they may grow catastrophically, leading to structural failures.

1.1. Existing literature on multiple delaminations

The impact of laminated and multilayered plate structures has been studied extensively (see Abrate, 1997, 1998 for reviews), as has the problem of single dynamic delamination fracture (Kanninen, 1974; Bilek and Burns, 1974; Freund, 1977; Hellan, 1978a,b, 1981, among the early works using beam/plate theory approaches; Sankar and Hu, 1991; Sridhar et al., 2002; Corigliano et al., 2006, among the more recent works). While several authors have formulated models that have the capacity of analyzing multiple delaminations (Williams and Addessio, 1997, 1998; Zou et al., 2001; Alfano and Crisfield, 2001; Aoki et al., 2007), few have proceeded to do so, perhaps because the complexity of the problem leads to burdensome analyses and makes it difficult to draw general and insightful conclusions. For quasi-static problems, Larsson (1991) and Suemasu (1993) showed the important influence of contact between the delamination surfaces in multiply delaminated structures subject to in-plane loading; Larsson (1991) and Zheng and Sun (1998) highlighted amplification and shielding effects in delamination interactions; and Suemasu and Majima (1996) noted that systems of equally spaced, equally sized, penny-shaped delaminations in homogeneous circular plates subject to a transverse point force maintain their equal sizes during propagation. No papers report studies on dynamic multiple delamination fracture.

Recently, the authors analyzed multiple delamination fracture of homogeneous plates subject to quasi-static cylindrical bending using a semi-analytic particularization of Timoshenko beam theory (Andrews et al., 2006; Andrews and Massabò, 2007, 2008; Andrews, 2005). Important interaction effects were detailed: (i) the presence of multiple delaminations induces phenomena of static amplification or shielding of the crack tip stress intensity factors

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(i.e., increase or decrease, respectively, relative to the value for the affected quasi-static crack when it is present alone in the same specimen) and modification of the mode ratios, even when crack tips are far from each other; (ii) amplification and shielding influence the macrostructural response, leading to snap-back and snap-through instabilities, crack arrest, crack pull along and strengthening effects (ultimate load exceeding the critical load for initial crack propagation); (iii) homogeneous systems of equally spaced, equal length delaminations subject to point forces always grow with equal lengths and the equality of length is stable with respect to length perturbations, whereas systems of unequally spaced delaminations can be unstable with respect to one becoming dominant. Further to the last point, the stability of the equality of length of a crack system is controlled by the spacing of the delaminations only (not by the initial length or the crack growth criterion); when lengths do not remain equal, load curves exhibit more brittle post-peak responses.

1.2. Scope of the present paper

In many structural applications, the loading conditions of most concern are dynamic or cyclic, rather than static. In the present paper, the prior results for static loading are used as a base to build understanding of multiple delamination under dynamic conditions. While many features of the static solutions remain present, substantial effects arise from inertia and cause qualitative changes in behavior in some regimes. In particular, dynamic amplification of the fracture parameters arises, i.e., increase relative to the values for the same crack system in static conditions. The dynamic amplification couples nonlinearly with crack interaction effects (characterized by the values of static amplification or shielding).

The problem studied is that of a multiply delaminated plate subject to cylindrical bending, which implies plane strain conditions and translational invariance of crack shapes in the direction of the bending axis. This geometry is different to that expected in the important engineering problem of laminated plates subjected to a point impact load, where induced delaminations typically show a staircase or pine-tree configuration that is partly controlled by the ply lay-up (e.g., Case and Reifsnider, 1999). Such crack configurations are not plane strain cases. The primary motivation for studying plane conditions is that they represent many laboratory tests: a logical path to predicting cracking in cases of general symmetry is first to deduce dynamic fracture properties, e.g., dynamic fracture energies or dynamic cohesive laws, from plane tests, which are easier to analyze, and then use those laws in a fully three-dimensional simulation of the field case. One important contribution of the present work is to provide enough understanding of the expected delamination behavior in such tests that specimen sizes, notch sizes, and loading histories can be chosen to assure that a test yields the desired data. Key issues include choosing tests that ensure the presence of multiple delaminations so that their effect on cohesive laws can be measured.

Cases presented include plates with various boundary conditions, including plates loaded transversely at mid-span with two built-in ends (“clamped–clamped”), two simply supported ends, or mixed end conditions, and a cantilever loaded transverselly at its free end (the cantilever case is used for a validation study of the solution method). With the exception of the validation study, all the results reported in detail are for the plate loaded at mid-span with two built-in ends, but occasional summary reference will be made to results for other cases.

Such cases do also resemble one important field case, namely that of a skin structure supported by stiffening ribs, such as an airframe, ship hull, or armored vehicle shell. Dynamic loads imposed at mid-span, as assumed here, might represent a ballistic impact, underwater blast, or blast in air.

For physical consistency under plane conditions, the plate and all sub-laminates created by delaminations are assumed to be orthotropic, with axes of elastic symmetry aligned with the specimen. This assumption allows the model to represent cases of interest in cross-plied fiber composites, provided plies are symmetrically grouped in sub-laminates, as well as mixed laminates of fiber composites and alloy layers, which are becoming widespread in airframes. Specimens satisfying the assumed constraint on symmetry can be assured in a composite specimen being used for calibrating dynamic bridging laws by choosing the lay-up appropriately or by using starter notches to restrict the active delamination planes.

1.3. Choice of formulation in the present work

An approximate formulation is used that yields analytic or semi-analytic solutions in the quasi-static case and considerably simplified computations in the dynamic case. The computational solutions are found by a finite difference scheme, which is very efficient for solving the differential equations that result from the assumed beam representation of displacement fields. The solutions are confirmed by finite element solutions, where the full 2D displacement fields are represented numerically, proving their accuracy in all but a few details of near-crack-tip fields that have no significant influence on the results. The approximate method allows the boundaries of different behavior domains to be mapped exhaustively and accurately. This is not easily done with 2D finite element solutions, due to numerical noise, which can obscure which behavioral domain a particular case belongs to.

The approximate method derives from the models formulated in (Andrews et al., 2006; Andrews and Massabò, 2007; Andrews, 2005) for the quasi static problem in which the system is decomposed into a discrete set of Timoshenko beams. In the present work, the formulation is extended by representing all fracture planes (actual and potential) through cohesive interfaces, which facilitates the computational creation of new fracture surfaces and allows for the study of multilayered systems. The cohesive interfaces may be used to represent the nonlinear process of material rupture, crack shielding due to through-thickness reinforcement, the elastic resistance to interpenetration of delaminated sub-laminates and the effects of friction. In this work, they are used to represent only the first three of these phenomena; and where the cohesive law represents matrix failure during delamination, it is chosen to correspond to perfectly brittle propagation of pre-existing cracks. Generalization of the law to allow prediction of the initiation of systems of delaminations (Williams and Addessio, 1998) as well as the treatment of friction is anticipated in future work.

The cohesive interface law is assumed here to contain an initial linear regime preceding the peak cohesive traction, beyond which the tractions vanish or diminish. Laws of this type were proposed by Xu and Needleman (1994) to study dynamic fracture in homogeneous materials and allow fracture to be a natural outcome of the boundary value problem. No special condition needs be imposed at the crack tip to predict crack initiation or propagation; the crack propagates when the local stress exceeds the peak traction in the cohesive law. The initial linear regime does allow some displacement discontinuity even in intact portions of the plate, which is non-physical, but the initial stiffness is assigned a very high value and the cohesive elements are introduced on only a few potential fracture planes, so the effect on the overall plate compliance is negligible. For the problem at hand the method is computationally simpler than the adaptive method (Camacho and Ortiz, 1996), in which the cohesive interfaces are inserted only when an external criterion to initiate and propagate fracture is satisfied.