INFLUENCE OF LARGE SCALE CRACK WAKE MECHANISMS ON THE DYNAMIC FRACTURE OF MULTIPLY DELAMINATED BEAMS

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Abstract

The paper deals with the dynamic interaction of multiple delaminations in composite plates subject to out of plane loading. In order to develop a basic understanding of the problem, the work refers to the model system of a multiply delaminated plate deforming in cylindrical bending. Interaction effects on fracture parameters, dynamic crack growth, energy absorption and damage and impact tolerance are investigated. Large scale crack bridging mechanisms, such as those produced by a through-thickness reinforcement, strongly control and regularize the dynamic response of systems of stationary delaminations. In the free vibration phase that follows the removal of the load, the crack bridging action developed by a typical through-thickness reinforcement can prevent out of phase vibrations and hammering of the delaminated layers and eliminate the associated large amplifications of the fracture parameters.

1 Introduction

Delamination and interfacial fracture are critical failure mechanisms of composite laminates and layered systems. Delamination fracture can occur as a localized event (single delamination) or as a diffuse event (multiple delamination). Multiple delamination is the typical consequence of severe dynamic loading, such as blast, impact and shock.

The interaction of multiple delaminations has important effects on fracture parameters, crack growth and macrostructural response. In addition, it strongly influences energy absorption capabilities, damage and impact tolerance, strength and stiffness.

In order to develop a basic understanding of the effects of the interaction of multiple delaminations, the exemplary case of a plate subject to cylindrical bending (Fig. 1) has been examined in [1-4] and interaction effects have been studied for quasi-static and dynamic loading conditions assuming the material to be perfectly brittle and contact between the crack surfaces to be frictionless. The main conclusions of [1,4] are presented in sections 2 and 3. The current work aims at investigating dynamic interaction effects in the presence of large scale bridging and cohesive mechanisms such as those generated by a through-thickness reinforcement. The main effects of large scale crack bridging mechanisms on the dynamic response of systems of stationary delaminations are presented in section 4.

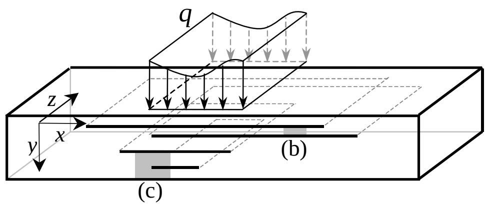


Fig. 1. Multiply delaminated plate deforming in cylindrical bending

2 Interaction effects of multiple delaminations in plates subject to quasi-static cylindrical bending

In the models formulated in [1,2,4] to study the interaction effects of multiple delaminations in plates subject to quasi-static loading conditions, the material is assumed to be homogeneous, orthotropic, linearly elastic and perfectly brittle. The plate of Fig. 1 is decomposed into multiple uncracked beam segments defined by the delamination planes. Timoshenko beam theory is used to describe the beam segments and continuity conditions are applied between beam segments. The near tip deformation is accounted for through localized elastic root rotations that define the relative rotations of the crack tip beam segments as functions of the crack tip stress resultants and numerically determined compliance coefficients [5]. Nonfrictional contact between the crack surfaces is simulated using a Winkler foundation approach. Mode decomposition is performed using the semi-analytical method of [5].

The presence of other delaminations induces phenomena of amplification and shielding of the energy release rate of a delamination and modifies its mode ratio. These phenomena are long range and controlled by the spacing of the delaminations. Amplification and shielding of the energy release rate then lead to snap-back and snap-through instabilities and phenomena of crack arrest, crack pull along and hyper-strength in the macrostructural response.

The stability of the equality of length of systems of equal length delaminations is controlled by the spacing between the delaminations. Systems of equally spaced delaminations grow self-similarly, while maintaining the equality of length, and are stable with respect to length perturbations; systems of unequally spaced delaminations can be unstable and controlled by the localized growth of one or a few delaminations; this behavior leads to more brittle responses with reduced energy absorption. Maps that synthetically describe the response of systems with two delaminations have been derived in closed form (Fig. 2).

3 Dynamic interaction effects of multiple delaminations

A model for the dynamic multiple delamination of layered plates subject to cylindrical bending has been formulated in [2,3]. The delaminated plate is modeled as a set of Timoshenko beams connected through cohesive interfaces apt at describing perfect adhesion in the intact portions of the plate, perfect decohesion and process regions where nonlinear crack face mechanisms may take place. The problem is solved with a finite difference scheme.

Dynamic interaction effects have been studied in systems of stationary and propagating delaminations in plates subject to concentrated transverse forces. The material has been assumed to be homogeneous, orthotropic, linearly elastic and perfectly brittle.

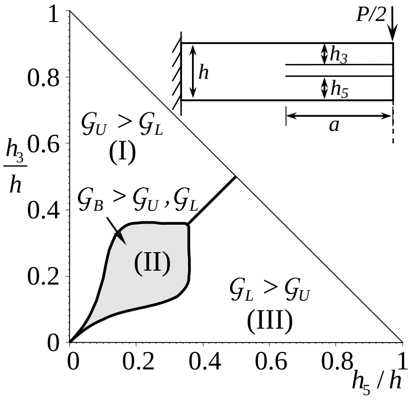


Fig. 2. Map of relative energy release rates in a two delamination system (clamped-clamped beam; homogeneous, isotropic, perfectly brittle material; contact as a Winkler foundation). If the position of the delaminations falls into the grey region, the delaminations propagate together and the equality of length of the system is stable; if the position falls into the white regions, growth is characterized by the propagation of only one of the delaminations.

In systems of stationary delaminations, interaction effects on the fracture parameters due to the presence of multiple delaminations couple with dynamic interaction effects. The characteristic feature of systems of equal length, equally spaced delaminations is that the deformation field remains essentially mode II at all times as a consequence of the symmetry. In addition, if the duration of the pulse is sufficiently long, dynamic amplification effects and amplification effects due to the interaction of multiple delaminations are essentially uncoupled.

The characteristic feature of systems of unequal length or unequally spaced delaminations, which include the case of single off-center delaminations, is that the dynamic response strongly varies over time and three characteristic regimes can be identified. During the loading phase (forced vibrations) the mode I components of the energy release rates of the delaminations always remain at or below the static values and only the mode II components are strongly amplified by dynamic effects. In this phase the delaminated arms of the plate are constrained to displace together. Strong amplifications of the mode I components of the energy release rates occur during the free vibration phase, after the load has been removed. This behavior is caused by the mismatch in bending stiffness of the delaminated arms that vibrate out of phase. The plate then enters a third regime of behavior characterized by localized impacts at different points along the crack surfaces and at different time steps (hammering). Because of the hammering, both components of the energy release rates present high frequency oscillations with large amplitudes. The diagram of Fig. 3 highlight this behavior in a system with a single off-center delamination.

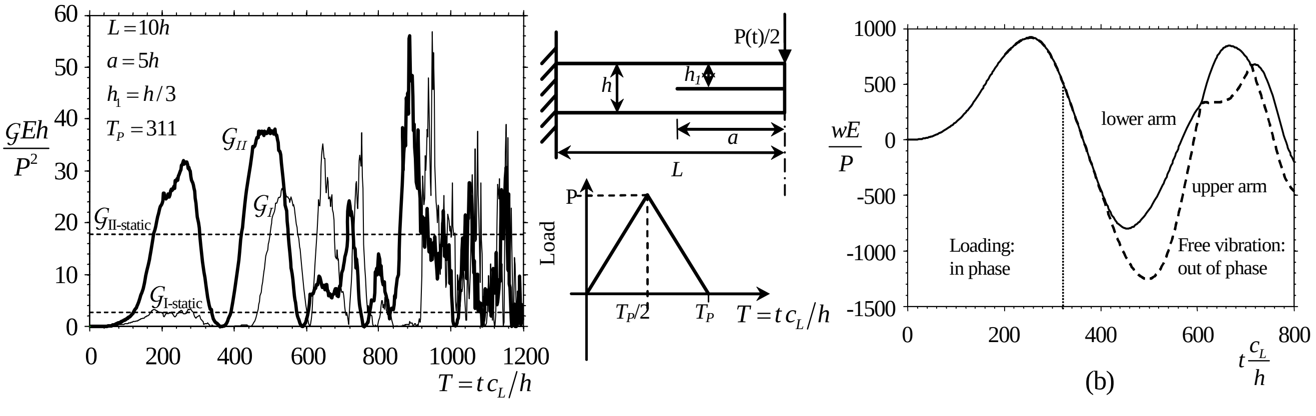
Diagrams of the time history of the energy release rate of stationary systems are useful to infer how systems of propagating delaminations will behave. If the initial propagation of the delaminations occurs during or after the forced vibration phase will determine different growth characteristics.

Systems of equally spaced, equal length delaminations always grow self-similarly under general dynamic loading conditions. The diagram of Fig. 4 highlight this behavior for a system of three delaminations in a clamped-clamped plate subject to a step force. On the other hand, systems of equal length and unequally spaced delaminations can be characterized by the localized growth of only one or few delaminations. An example of this behavior is presented in Fig. 5. As for the quasi static case, the through-thickness position of the delaminations determines wheter the system will grow self-similarly. The map of Fig. 2, obtained in closed form under quasi-static loading conditions, proves to be applicable to systems subject to dynamic loading when the initial propagation of the delaminations occurs during the loading phase.

If the initial propagation occurs after the load has been removed, in the free vibration regime, localized growth can occur also in systems whose delamination position falls into the grey regions of the map in Fig. 2. However, in these cases crack growth is a consequence of phenomena of localized impact along the delaminated surfaces (see Fig. 3) and is therefore extremely slow, sporadic and in general negligible.

4 Influence of large scale crack face mechanisms on dynamic interaction effects

Bridging and cohesive mechanisms acting over large regions along the crack surfaces strongly influence the fracture characteristics, the macrostructural response and the mechanical properties of layered systems. These mechanisms can represent the action developed by a through-thickness reinforcement, such as stitching or z-pins. The through-thickness reinforcement creates large regions of bridging along the wake of the delaminations that shield the crack tip from the applied loads thus reducing the driving force for crack propagation or even suppressing crack growth. A through-thickness reinforcement can reduce the loss of stiffness due to delamination, modify modes of failure and prevent catastrophic collapses of the structural components.



(b)

(a)

Figure 3. Off-center delamination in a clamped-clamped beam subject to a triangular loading pulse of normalized duration $T_P = t_P c_L/h = 311$ (c_L = longitudinal wave speed) or $T_P = 3/4\ T_1$, with $T_1 = 415$ the first normalized natural vibration period of the beam (calculated assuming constrained contact). (a) Time history of the energy release rate; (b) Time history of the transverse displacements of the delaminated arms at the mid-span. (The material is homogeneous and isotropic; contact is simulated using a Winkler foundation approach; no other cohesive or bridging mechanisms are present).

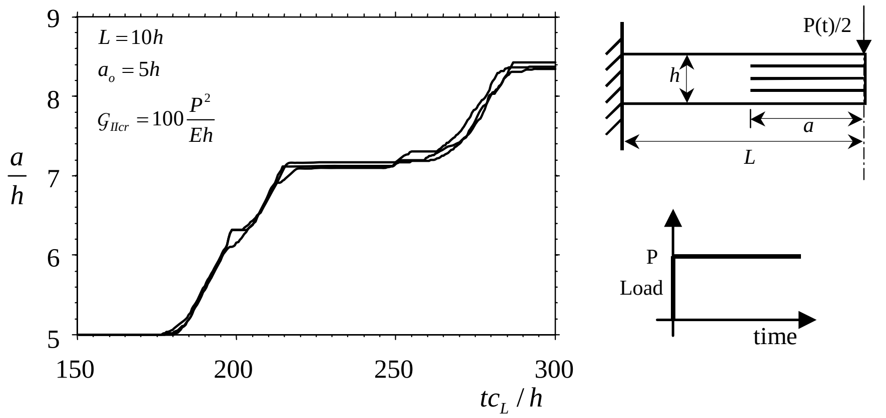


Figure 4. Crack growth history in a clamped-clamped system with three equal length equally spaced delaminations subject to a step load. The system grows self-similarly and the equality of length is maintained at all times (see also the stability map of Fig. 2). (The material is homogeneous and isotropic; contact is simulated as a Winkler foundation; no other cohesive or bridging mechanisms are present).

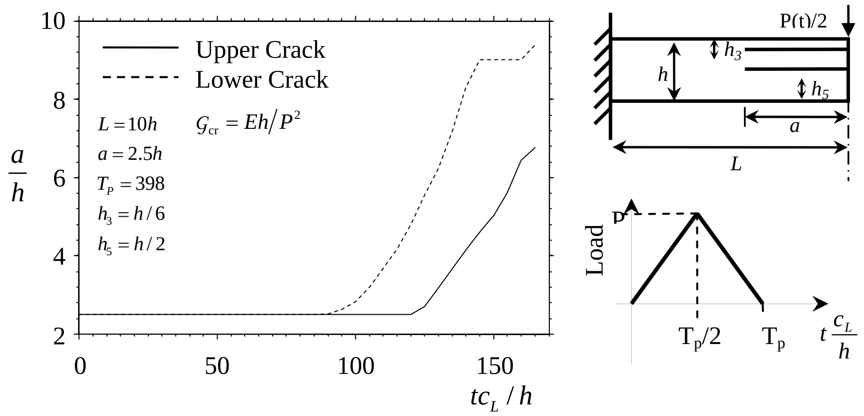


Figure 5. Crack growth history in a clamped-clamped system with two equal length, unequally spaced delaminations subject to a triangular loading pulse of normalized duration $T_P = T_1 = t_1 c_L/h = 398$ (c_L = longitudinal wave speed) with T_1 the first normalized natural vibration period of the beam (calculated assuming constrained contact). Crack growth is characterized by the localized growth of only one of the cracks that propagates over a long distance before the other crack starts to propagate (see also the stability map of Fig. 2). (The material is homogeneous and isotropic; contact is simulated as a Winkler foundation; no other cohesive or bridging mechanisms are present).

The effects of large scale crack bridging in singly delaminated systems subject to quasi static loading conditions have been studied extensively in the literature (see for instance [6,7,8] and references therein). On the other hand, the influence of large scale bridging mechanisms on the dynamic response of multiply delaminated systems is not well understood and most of the published work deals with singly delaminated systems (see for instance [9,10] and references therein).

In this section, preliminary results describing the response of systems of stationary delaminations in the presence of large scale bridging will be presented. The bridging mechanisms are modeled as uniform distributions of linear elastic springs that oppose the relative displacements between the crack surfaces and exert symmetric restoring forces during vibration. The bridging tractions acting normally and tangentially to the crack surfaces, T^N and T^S, are then related to the relative opening and sliding displacements, w^N and w^S, by the linear proportional laws:

$$T^N = k^N w^N$$
$$T^S = k^S w^S \qquad (1)$$

where k^N and k^S are the normal and tangential stiffness of the springs. If the relative displacements between the crack faces are not too large, the linear bridging laws in (1) well describe the bridging mechanisms produced by a through-thickness reinforcement [10,11,12].

The diagram of Fig. 6 describes the time history of the energy release rate components of the stationary delaminated system shown in the inset and already studied in the absence of crack wake bridging mechanisms in Fig. 3. The diagram refers to crack bridging mechanisms described by Eq. (1) with $k^S = 0.01\,E/h$ and $k^N = 0.01\,E/h$. The value assumed for k^S has been chosen to correspond to a typical stitched composite laminate as shown in [10,11,12] (carbon/epoxy quasi-isotropic laminate, 48-ply, total thickness 7.2 mm, stitched with glass fiber tows in a square array of side 3.2 mm, stitch area fraction = 0.062; effective longitudinal Young's modulus E = 49 GPa, shear modulus of G = 2.6 GPa). The normal stiffness k^N is typically larger than k^S and has been put equal to k^S to highlight important characteristics of the response. The thin dashed lines in the diagram correspond to the solution of an unstitched laminate (Fig. 3).

The diagram shows that large scale crack bridging mechanisms have two important effects on the response of the system. During the forced vibration phase, the presence of crack bridging shields the energy release rate components and has an important influence on the mode II component that is strongly amplified by dynamic effects in the absence of a through-thickness reinforcement. The shielding effect is controlled by the stiffness of the springs and increases on increasing k^N and k^S (for instance by increasing the area fraction of through-thickness reinforcement). During the free vibration phase that follows the removal of the load, the crack bridging mechanisms have an important effect on the response since they prevent out of phase vibrations and hammering of the delaminated arms of the plate. As a consequence, the high frequency, high magnitude oscillations observed in Fig. 3 are eliminated, the response becomes more regular and the oscillations in both the mode I and mode II components of the energy release rate become periodical. This effect is mainly due to the normal bridging tractions that oppose the relative crack opening displacements. It is worth noting that very small values of k^N, namely $k^N > 0.001\,E/h$, are enough to regularize the free vibration response and that increasing this value to the assumed

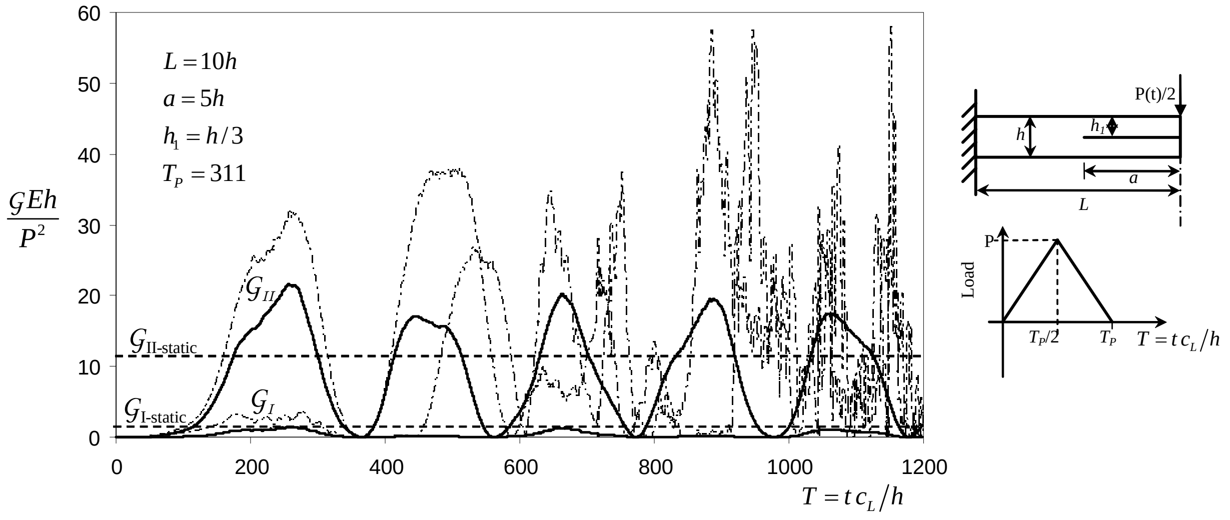


Figure 6. Time history of the energy release rate components of a clamped-clamped system with an off-center delamination in the presence of linear proportional crack wake bridging mechanisms with normal and tangential stiffness $k^S = 0.01\,E/h$ and $k^N = 0.01\,E/h$. The system is subject to a triangular loading pulse of normalized duration equal to 3/4 of the first natural vibration period of the system in the absence of a through-thickess reinforcement . (The material is homogeneous and isotropic; contact is simulated as a Winkler foundation).

$k^N = 0.01\,E/h$ or higher has the only additional benefit of shielding the mode I component of the energy release rate and has no effect on the mode II component.

5 Conclusions

Dynamic interaction of multiple delaminations has important effects on the response of layered systems subject to out of plane loading. This behavior has been studied referring to the model system of a plate deforming in cylindrical bending and applying the model formulated in [1-4] that uses Timoshenko beam theory.

When contact is the only crack face mechanism acting in the plate, characteristic features of the response to dynamically applied loads of stationary systems of delaminations of unequal length or unequal spacing are the out of phase vibrations and hammering that are present in the free vibration phase following the removal of the load. Out of phase vibrations and hammering lead to high frequency, high magnitude oscillations in the time history diagrams of the energy release rate components.

In the presence of large scale crack face bridging mechanisms, such as those developed by a through-thickness reinforcement, the dynamic response of the system changes substantially. As for the quasi static case, the bridging mechanisms shield the crack tip from the applied loads so that both mode I and mode II components of the energy release rate decrease. In addition, the bridging mechanisms regularize the response in the free vibration phase by preventing the out of phase vibrations and hammering of the delaminated arms of the plate. As a consequence the large amplifications of the energy release rate components that characterize the response of systems in the absence of bridging mechanisms are eliminated.

It is expected that large scale bridging mechanisms will have important effects also on the response of propagating systems of delaminations. This problem is currently being investigated.

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