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Effects of voids on postbuckling delamination growth in unidirectional composites

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ABSTRACT

This work examines the effects of manufacturing induced voids on the postbuckling behavior of delaminated unidirectional composites. In the finite element model developed, a through-width delamination is introduced close to one surface of a flat panel, and a void is placed in the delamination plane ahead of each delamination front. The panel is subjected to compression in the fiber direction. The postbuckling delamination growth is studied by calculating the strain energy release rate (SERR) using the virtual crack closure technique. Local stress analyses of the region near the delamination front are also performed to further investigate the void effects. It is found that although the presence of void does not significantly alter the postbuckling transverse displacement of the delaminated panel, the induced stress perturbation by the void affects the SERR. The Mode II SERR as well as the total SERR increase depending on the size of the void and its distance from the delamination front. Since the Mode I SERR shows non-monotonic behavior with the applied load, the effects of voids are studied on its maximum value.

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1. Introduction

Composite materials continue to be applied in a wide range of load bearing structures due to their attractive properties. Many of these structures have a laminated construction, which is prone to local delamination caused by impact, manufacturing defects or discontinuities, leading to degradation of structural performance (Garg, 1988). For a delaminated structure subjected to in-plane compression, the delamination region may buckle out of the plane when the compressive load reaches a critical value and an increase in this load can cause further growth of delamination resulting in final failure.

Chai et al. (1981) were the first to develop a one-dimensional model to study the postbuckling deformation of laminated plates. Later, Kyoung and Kim (1995) included transverse shear deformation in the analysis and found the dependence of buckling load on delamination configuration. Whitcomb (1981, 1984) used two-dimensional finite element analysis to study the postbuckling deformation and the influence of delamination configuration. Besides such analytical and numerical investigations, some experiments were also conducted to characterize the postbuckling behavior (Kardomateas, 1990). Single versus multiple delaminations have also been studied, and depending on the configuration of multiple delaminations, significant differences in the buckling behavior were found (Kutlu and Chang, 1995; Lim and Parsons, 1993; Suemasu, 1993). However, for relatively long delamination near the surface, it was found that the buckling behavior of multiple delaminations was almost the same as that of a single delamination (Hwang and Liu, 2001).

In composite materials, voids inevitably exist induced by manufacturing. Many experiments have shown that mechanical properties such as interlaminar shear strength, fatigue resistance and compressive strength decrease with increasing void content (Bowles and Frimpong, 1992; de Almeida and Neto, 1994; Ghiorse, 1993; Judd and Wright, 1978; Suarez et al., 1993; Wisnom et al., 1996). In spite of the overwhelming evidence, relatively few models are available to analyze the effects of voids. Based on the beam theory, Hagstrand et al. (2005) found that the presence of voids had a detrimental effect on the flexural modulus and strength. Huang and Talreja (2005) proposed a computational model to assess the effect of void geometry on elastic properties of unidirectional composites and showed that the voids have much larger influence on reducing the out-of-plane properties than the in-plane ones. Recent studies (Lambert et al., 2012; Ricotta et al., 2008) have indicated that the void content by itself is inadequate to explain the effect of voids. Instead, factors such as size and shape of voids, as well as their location, must be considered. In fact the effect of voids and other defects such as fiber waviness and irregular fiber distribution in initiating damage and the interaction

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between damage and defects have prompted a new field called "defect damage mechanics" (Talreja, 2009) for assessing the effects of defects on composite performance.

This paper presents results of a parametrical study of the effects of voids on the postbuckling behavior of a unidirectional composite panel with a through-width delamination. Recent investigations on voids (e.g., Lambert et al., 2012) have indicated that extremes in the distribution of voids and their placement in critical areas are important factors in affecting the composite performance. As a result, instead of studying distributed voids throughout the volume and their averages, we choose to focus here on the critical effects of the voids in terms of their size and placement. Thus we place one void each ahead of the two fronts of the delamination lying parallel and close to the surface of the panel loaded in axial compression and in the parametric study vary the size of the voids and their distance from the delamination front. For a single delamination, local buckling usually occurs at a lower load than global buckling (Wang and Zhang, 2009). The effect of voids on strain energy release rate (SERR, denoted G) is calculated to represent the driving force for delamination growth. The local stress field near delamination front is also studied in order to further understand the effects of voids.

2. Model description

We model the problem as a 2-D composite plate with fibers in the longitudinal direction containing a single through-width delamination close to one of the plate surfaces. For comparison purposes, the material properties taken are those used in Whitcomb (1984) (Table 1). The plate is assumed to be clamped at both ends and loaded in axial compression. The dimensions used in the model are labeled in the 2-D section of the plate in Fig. 1, and are as follows. Plate length $2L$ = 100 mm, thickness H = 2.0 mm and width (not shown in Fig.1) is assumed to be 20 mm; delamination length $2a$ = 30 mm, and the shorter distance of delamination from the plate surface t = 0.25 mm. For the selected dimensions of the plate and delamination, and the distance of delamination from the surface, local buckling is expected to occur under axial compression.

To study the effect of manufacturing induced voids on the local buckling of the plate, one void is placed ahead of each delamination front in the delamination plane, as the position of the void in this plane is expected to influence the stress field at the delamination front more than positions of the same void in other locations for a given distance from the delamination front. The distance of the center of void from the delamination front, denoted by d, is used as a variable. Although in reality the voids have a 3-D geometry, in the 2-D finite element (FE) model used here, the voids are modeled as a through-width cutout region parallel to the delamination front. Images of voids situated in interfaces between plies in unidirectional composites manufactured from pre-pregs are shown on Fig. 2. As described in Huang and Talreja (2005), most of the these voids have elongated cylindrical, cigar-shaped geometry running along the fiber direction. Hence, in our model, for simplicity and to adapt the void shape to the 2-D case, the section of the void parallel to the fiber direction is modeled as a rectangle with semi-circular caps at both ends, as illustrated in Fig. 1. The void dimensions L_v and h_v are depicted in Fig. 1.

A 2-D geometrically nonlinear FE analysis was performed using the commercial software ABAQUS. For the model shown in Fig. 1, Because of the symmetry, half of the plate was modeled and symmetry boundary conditions were imposed on the plane $X = 0$. At the bottom of the plate, displacement along the Y-direction was constrained in order to induce local buckling. At the end of the plate, L = 50 mm, uniform axial displacement was applied to simulate the compressive load. Eight node plane strain quadrilateral elements were used near the delamination front, and reduced integration scheme was implemented in order to improve the performance of the 2-D elements. As recommended for the virtual crack closure technique (VCCT), the region near delamination front was modeled by symmetrically regular shaped elements of uniform size, as indicated in the FE mesh shown in Fig. 3, and the smallest element size was chosen as e = 0.0125 mm.

It is noted that we did not impose the contact constraint in the model for the following reason. As described in Whitcomb (1981) for near-surface delamination, the competitive interaction between the delamination front opening and closing moments, caused respectively by the increase of lateral deflection and the eccentricity in load path measured from the initial to the buckled configuration, leads to the delamination front opening first and then closing locally with the increase of the applied load. This results in the non-monotonic variation in G_I (to be shown later). Since contact constraint was not imposed in the model, this would result in potential delamination face overlap in the FE analysis when the delamination front is closing. However, it was found that the maximum G_I was reached while delamination front was still open and thus there is no contact between delamination faces at that point. After reaching the G_{Imax}, if the delamination front starts to close locally with increasing applied load and delamination face

Table 1
Elastic material properties (Whitcomb, 1984).

E_{11} (GPa)	E_{22} (GPa)	G_{12} (GPa)	υ_{12}
140	14	5.9	0.21

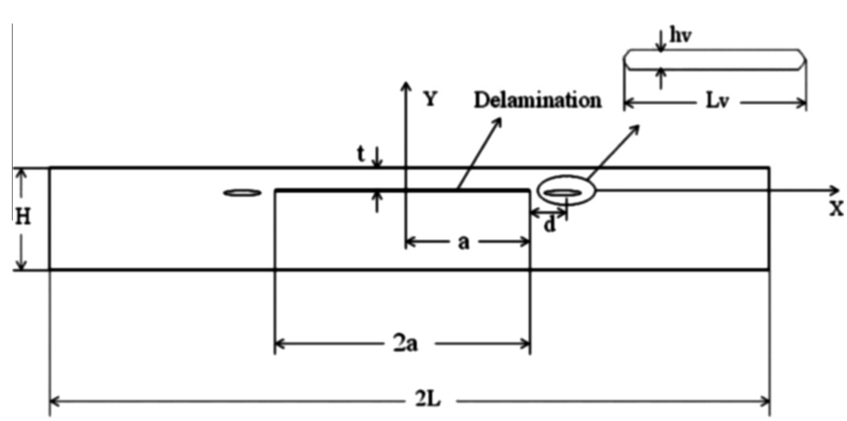

Fig. 1. Schematic illustration of the model.